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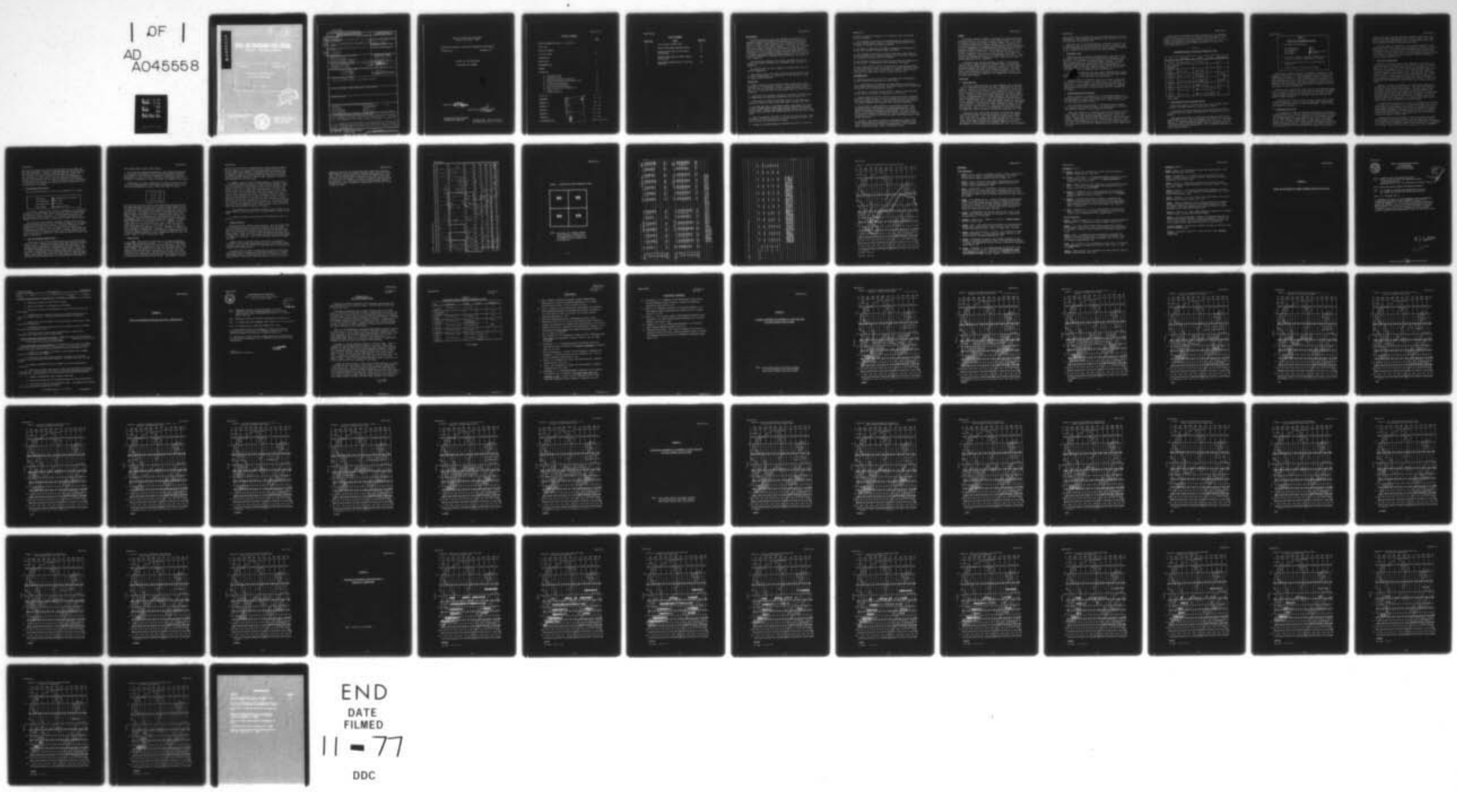

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Icing

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A literature survey was conducted to define the possible hydrometeorological conditions during which icing of the gas turbine inlets of a ship could occur. Also included is a list of all sources of information used during the survey.

A frequency-of-occurrence study of the icing conditions found during the literature survey was also done and the results included as maps of the North Atlantic. The North Atlantic was chosen as it gave the most complete data base available at the time.

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NAVAL AIR PROPULSION TEST CENTER
Trenton, New Jersey 08628

PROPULSION TECHNOLOGY AND PROJECT ENGINEERING DEPARTMENT

NAPTC-PE-114 SEPTEMBER 1977

A SURVEY OF ICING CONDITIONS FOR MARINE GAS TURBINES

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INTRODUCTION

The Naval Ship Engineering Center (NAVSEC), Washington, DC, is presently conducting a program to evaluate marine gas turbine inlet separator systems. These systems are of the types used on the new classes of ships entering the fleet such as the DD-963 (Spruance), FFG-7 (O.H. Perry) and the PHM-1 (Pegasus). The Naval Air Propulsion Test Center (NAPTC), Trenton, NJ, is involved in a test program to evaluate such systems by the simulation of a controlled marine air environment. As a supplement to this evaluation, NAPTC was tasked to investigate the marine icing environment, define the icing conditions and make recommendations regarding the alleviation of its effects on inlet separators.

The project was authorized under Task D of NAVSEC Work Task Assignment No. 6146-2, Revision B, of 16 September 1975 (included as Appendix A).

An interim report was sent to NAVSEC on 16 March 1976 and is included as Appendix B.

This report presents the final results of the investigation and the NAPTC recommendations for dealing with the possibility of icing of marine aerosol separators.

CONCLUSIONS

1. Icing on ships is caused chiefly by spray, either wind or ship generated, or a combination of the two. It is this type of icing that will have the most detrimental effect on marine gas turbine inlets. Thus, it is the primary type of icing against which the inlets must be protected.

2. Supercooled fog, previously assumed to be the most probable cause of intake icing, is relatively non-existent over the open ocean.

3. Supercooled fog could be encountered close to a cold land mass; however, no record of intake icing under these conditions was found.

4. No record was found of condensate icing of ship engine inlet bellmouths or Foreign Object Damage (FOD) screens, although theoretically it could occur. However, past experience with screens in aircraft gas turbine inlets has shown they rapidly collect ice, and they are no longer used.

5. There are basically two types of ice that are found on ships: rime and glaze. Of the two, glaze ice is the most dangerous because of its greater density and high adhesive strength.

6. A range of hydrometeorological conditions necessary for icing can

be found by taking the extremes of the conditions that existed when icing was reported.

7. The frequency-of-occurrence of hydrometeorological conditions in the North Atlantic Basin, capable of causing icing, is highest during the months of November thru March, inclusive.

8. The month of January has the highest frequency-of-occurrence and largest area coverage over which icing could occur.

9. The frequency-of-occurrence of icing conditions is high enough in the North Atlantic that a ship operating in this region will encounter such conditions sometime during its lifetime.

10. The farthest distance from a land mass over which sub-freezing temperatures occur is approximately 1,300 kilometers (808 miles).

11. Due to the relative scarcity of information on the physical makeup of icing conditions of ships, as compared to aircraft icing where liquid water content, droplet size distribution and length of time of icing conditions are known, more research is needed in this area.

RECOMMENDATIONS

1. Marine gas turbine inlets should be designed with consideration towards incorporating some means to combat icing.

2. A system should be incorporated to either anti-ice or de-ice the engine inlet bellmouth and screen. This system should only be needed when the possibility of condensate icing exists.

3. De-icing or anti-icing systems should be capable of providing protection down to an ambient air temperature of -15°C (5°F).

4. Engine intakes and demister systems should be sited in a protected area on the superstructure. The most preferable position is facing inboard and as high as possible. This would have the additional benefit of protection against salt ingestion under non-icing conditions.

5. Blow-in doors or some alternate air source which by-passes the demisters should be incorporated as a precautionary measure. These doors should include provisions for keeping them free of ice and be capable of handling the necessary engine airflow. The blow-in doors can be actuated either automatically by sensing the pressure drop across the demister or manually by alerting the ship's crew when pressure drop becomes excessive.

6. Because of the relative scarcity of information on intake icing, at-sea testing should be conducted to verify the performance of the ship's intake system under actual icing conditions. This evaluation could be conducted during a ship's cold-weather trials.

SUMMARY

A study was conducted at NAPTC to determine the hydrometeorological conditions likely to cause icing of ships' intake systems. This study was primarily conducted through a literature search using the resources of the Defense Documentation Center, Cameron Station, Alexandria, VA, and reports obtained from the Naval Ship Engineering Center, Philadelphia Division, Philadelphia, PA (NAVSECPHILADIV); the Naval Weather Service Detachment (NWSD), Asheville, NC; other government agencies U.S. and foreign; and private contractors. Due to the relative scarcity of information regarding icing of ships' intake systems, much reliance was based on information regarding icing of other ships' structures. It was assumed that the causes of icing on the ships' superstructure would be equally applicable to the separators.

In addition to the literature search, a frequency-of-occurrence study was made by NWSD for the North Atlantic Ocean. This area was selected for the study primarily because it provided the most complete hydrometeorological data base of the world's oceans due to the large amount of shipping that takes place through this region. The study used a range of parameters obtained from the literature search. The parameters used were air temperature, sea temperature, wind speed and sea state (wave height).

DISCUSSION

A. Supercooled Fog

Icing due to supercooled fog, the most prevalent cause of aircraft icing, is relatively non-existent on ships. Supercooled fog over the ocean is confined to the areas north of 60°N latitude and south of 60°S latitude. The period most likely to have supercooled fog is from November to February, inclusive, with December having the highest probability. During this four-month period, supercooled fog can be expected to occur on approximately 14 to 18 non-consecutive days (Reference 1). These probabilities are based on both open ocean and coastal observations. Inquiries made of U.S. Naval and private vessels, as well as of vessels operated by foreign nations that frequent this area, substantiate this observation. Ships are more likely to encounter supercooled fog while in port or off the coast of a cold land mass than while out on the high seas. This is due to the interaction of the sea-land interface where the coldest extremes of sea and air temperatures are found.

Supercooled fog is also known as "artic frost smoke" and occurs when the air is below 0°C and the difference in sea and air temperatures is at least 9°C. This "frost smoke" is called either "white frost" when it is only several feet thick or below eye level, and "black frost" when it extends above this (Reference 2). It is interesting to note that during the cold weather trials of the British HMS EXMOUTH, very bad weather was encountered and "black ice" accumulated

on the ship's upper superstructure, but the intakes stayed free of ice (Reference 3). The intakes on the EXMOUTH at the time were of the knit-mesh type made of woven nylon pads.

Should the face of the intake demisters experience icing-over due to supercooled fog, and this would seem to be a rare occurrence, blow-in doors incorporated into the design would suffice until the demisters could be cleared or the ship is out of the icing situation.

B. Condensate Icing

Condensate icing is caused by the appearance of free water in the air under a high humidity condition when the static temperature falls below 0°C. This phenomenon is quite common on aircraft, especially when the inlet duct is of considerable length. However, the usual ship engine installation consists of an FOD screen followed by a bellmouth intake and the short length of the bellmouth does not allow sufficient time for the water vapor to condense out of the air due to an apparent lack of nucleation sites (Reference 4).

Reference 5 mentions that the Coast Guard's HAMILTON class cutters have provisions to drop the protective screens over the engine intakes should icing occur, but have had no such experiences.

Although reports of condensate icing on ship engine intakes have not appeared in any literature, the potential for its occurrence is still there. If, for example, the engine intake design was such that length of the bellmouth was enough to allow free water to condense, then either an anti-icing or de-icing system should be installed on the engine.

C. Hydrometeorological Conditions

Table 1 (below) is a compilation of the hydrometeorological conditions conducive to icing from several of the reports reviewed. These are conditions that caused icing of the ships' superstructures from various locations around the globe.

Since difficulty was encountered in locating literature dealing with icing of inlet systems on ships, much reliance had to be made on the conditions reported to cause superstructure icing.

Taking the extremes of the values of the four parameters in Table 1 gives a range in which icing can be expected to occur. Within this range, there are three general categories defining the rate of ice buildup: slow, rapid, and very rapid (Reference 6). Slow icing usually appears at temperatures from -1°C to -3°C at any wind velocity. From -3°C to-8°C air temperature and winds up to 15 m/sec, rapid icing occurs. Very rapid icing occurs with air temperatures below -8°C and winds above 15 m/sec.

The minimum air temperature at which icing can occur is generally accepted as being -18°C due to the fact that the spray droplets freeze before striking the ship and do not adhere to the structure. This, however, only applies to wind-induced spray and may not be true for all of the spray generated by the mechanical action of the ship on the water (References 2 and 7).

Table 1

HYDROMETEOROLOGICAL CONDITIONS CONDUCIVE TO ICING

OAT	SEA TEMP	WIND	SEA*	REFERENCE #
-1.5°C to -17.7°C	Slightly < 0°C	> 9 m/sec	-	8
Lower Limit of -18°C	- -	-	-	9
0°C to -25°C	8°C to -2°	> 8 m/sec	-	10
-5.8°C to -12.7°C	2°C to -1.4°C	9 m/sec to 15.5 m/sec	-	1962 } 11
-1°C to -7.3°C	2.4°C to -0.4°C	9.7 m/sec to 15.5 m/sec	-	1963
-1°C to -14°C	3°C to -1.8°C	> 9.3 m/sec	-	12
-2°C to -7 °C	0°C to -2.5°C	> 4.4 m/sec	1.2 m to 2.4 m	13
-4°C to -14°C	2°C to -3°C	> 4.4 m/sec	0.30 m to 3.6 m	

* Wave height

D. Naval Weather Service Detachment Study

During the research, it became clear that a more in-depth survey of weather conditions conducive to icing had to be made.

Accordingly, the NWSD in Asheville, NC was asked to provide both bi-variate and multi-variate distributions of the conditions listed in Table 2.

NWSD presented the data by subdividing each Marsden Square of the Atlantic basin, north of the 30th parallel, into four 5° by 5° sections. Figure 1 is a Marsden Square map showing the area covered by the study. This map is used to show meteorological data over the ocean and is derived from the Mercator map projection. The 5° subsquare numbering system is shown in Figure 2.

Table 2

CONDITIONS FOR PROBABILITY STUDY

1. Meteorological Parameters

Air Temperature	$\leq$ 0°C
Sea Temperature	$\leq$ 5°C
Wind Speed	$\geq$ 17 knots (9 m/sec)
Wave Height	$\geq$ 3 meters

2. Area to be covered is the North Atlantic north of the 30° parallel divided into 5° squares.

3. Time coverage of data to be at least the past 10 years.

4. Output format to be for all 12 months.

Within each of these sub-squares is presented a breakdown of the frequency-of-occurrence of various combinations of wind speed and air temperature (see Figure 3). This percentage frequency is based on a total observation number (n) that is defined as the observations for which there was both a wind speed and air temperature value and it is unique for each sub-square. Each page represents a summary of all observations for that particular month and Marsden Square over the ten-year period from 1961 through 1970.

Figures 3 and 4 show typical study results from one Marsden Square. Figure 3 is the bi-variate distribution for wind speed and air temperature for square 116 and its four sub-squares for the month of March. A multi-variate distribution for the same square by sub-square and month is shown in Figure 4.

In analyzing the data, the effects of the ice pack on the results should be considered. Figure 5 shows the approximate southern limit of both the pack and drift ice in the North Atlantic. These effects are discussed in Section I.

E. Frequency-Of-Occurrence

It is important to make the distinction between the frequency-of-occurrence presented in the NWSD data and the probability-of-occurrence. Probability-of-occurrence is an extension of the percentage frequency-of-occurrence based on a larger amount of data that is continuous in nature. The data base obtained from an ocean station vessel where weather data is taken at least hourly and with consistent methods can give this continuous nature. Unfortunately, this cannot be said of the data here where much of the observations are reports from transient

vessels, both government and commercial, and were not taken on a regular basis or with consistent methods from ship to ship. Thus, this data can give only an approximate idea of the conditions that a ship will be exposed to while passing through an area.

This data should be interpreted to say that the conditions during which icing could occur exist a large percentage of the time, not that icing will occur. This concept can be demonstrated by the fact that the Canadian fishing fleet operates in an area of high icing condition occurrence, but only a small number of icing incidents are reported each year, despite a program that was instituted to gather information on icing incidents (Reference 14).

F. Bi-Variate Distribution

Because of the large amount of data generated in this survey, it became necessary to develop criteria to reduce the amount to a manageable size. First, all data output that did not have percentage frequencies at air temperatures 1°C or below with wind speeds higher than 5.7 m/sec (11 knots) were separated out. This data was further reduced by summing the percentages for the conditions with air temperatures less than or equal to 1°C and wind speeds greater than or equal to 5.7 m/sec and rejecting those with sums less than five-percent. The five-percent cut-off point was arbitrarily chosen as a figure that below which the probability of encountering such a situation was minimal.

Appendix C contains 12 frequency-of-occurrence maps showing the results after the data reduction process. The large block numbers are the Marsden Square identification numbers. The sub-squares contain two values, the upper value denoting the percentage frequency-of-occurrence and the lower value showing the total number of observations for the period of record taken within each sub-square. Any total observation number less than 100 was not used to determine occurrence because it was felt the average of 10 observations per month was not statistically valid to characterize the entire month.

As expected when looking over the maps, the frequency-of-occurrence of possible icing conditions was at a maximum during the winter months. From November through December, the frequencies increase then peak in January with the highest values and the most extensive area coverage of the winter icing season. February marks the start of a downward trend and by the end of April, the frequencies-of-occurrence are confined to the extreme northern waters.

Looking at the map for January, it can be seen that icing conditions can extend over quite a distance from the nearby land masses. This distance of approximately 1,300 kilometers (808 miles) is influenced by several factors, primarily, however, it is limited by the temperature of the ocean. Since the sea acts as a large heat sink, it gradually

warms the air passing over it that has blown out over the ocean from the frigid land mass. Reference 14 contains mean sea temperature maps that show this effect. However, working against this is the large extent of packed ice formed outward from the coasts (see Figure 5). This large area of frigid mass prevents the air from being warmed by the open ocean and also provides a maximum temperature differential between the air and the sea. As stated in Section A, this differential is conducive to the formation of supercooled fog and white/black frost so well known to trawlermen.

G. Multi-Variate Distribution

This distribution study was based on four parameters as follows:

Wind Speed	$\geq$9 meters/second (17 knots)
Air Temperature	$\leq$0°C (32°F)
Sea Temperature	$\leq$5°C (41°F)
Wave Height	$\geq$3 meters (9.8 ft)

As expected, because of the necessity of having all four parameters included in a single weather report, the total number of observations was smaller and not as extensive. The data reduction procedure used was basically similar to that for the bi-variate distributions and Appendix D shows the resulting frequency-of-occurrence maps produced.

The trend for these conditions naturally follows that of the bi-variate distribution with the peak occurring in January for the highest frequencies and largest area coverage. The major difference is that values are not as high for each sub-square due to the need for a simultaneous occurrence of the four limits. However, these values may be more indicative of icing conditions as most icing incidents seem to occur during low air temperatures, high winds and large sea states (see Table 1, Section D).

H. Low Air Temperature Design Point

After study of the results presented above, it was concluded that intake icing is a problem that a naval vessel would encounter sometime during its life. Subsequent discussions held with personnel at the Canadian Naval Engineering Test Establishment, Montreal, Quebec, and the National Research Council of Canada, Ottawa, Quebec, support this conclusion. The Canadian National Defence Department has adopted a policy of equipping their vessels with some method of combating ship's intake icing. NAPTC agrees with this policy and feels that the incorporation of either an anti-icing or de-icing system be considered in

naval vessel engine intake system designs.

One of the most important parameters in this design consideration is the lowest air temperature that a ship could encounter during normal operation. This minimum air temperature determines the maximum temperature rise that any type of de-icing or anti-icing system has to be capable of supplying to remove or prevent ice formation at the inlet.

Consequently, the data available from the NWSD bi-variate distribution study was manipulated to determine the frequencies-of-occurrence of low air temperatures by bands. These bands were as follows:

1°C to -2°C
-3°C to -6°C
-7°C to -10°C
-10°C and below

The data output was then summed in each temperature band ignoring the wind speed categories and the results plotted on maps similar to the bi-variate and multi-variate maps. Appendix E shows these results for the three most severe months of December through February in each temperature band. The number entered in each sub-square is the percentage frequency-of-occurrence for the temperature span shown on the figure. Figure 11 of Appendix E for the temperatures less than -10°C for January, shows that the maximum frequencies for the coastal area around Newfoundland is in the neighborhood of 20-percent. A minimum temperature would therefore appear to be -10°C. However, because of the nature of the study and the fact that it takes into account temperatures less than -10°C, a safety margin of -5°C was added to bring the lowest air temperature to -15°C. Reference 15 (pages 134 - 137) recommends a somewhat lower temperature, but this is only for the ship in an open port situation. It is therefore recommended that -15°C be used for design purposes, as lower temperatures would not occur frequently enough to cause a problem with icing.

I. Types of Ice

1. Rime. Rime ice can be identified by its opaque appearance, roughness and low adhesive strength. It is caused by the impactation of small supercooled droplets onto the ship's structure. The supercooled droplets can be generated by wind- or ship-induced spray. The most important consideration here is that the residence time of the droplet in the cold air mass is sufficient to cool the drops below freezing but not freeze them. When the droplets impact on the structure, they freeze instantly which causes air to be trapped in the ice accounting for the opaque and rough surface. Fortunately, this also

gives it its low adhesive strength and the ice can easily be removed by one's hand or by a brush passed over the surface, as long as it does not build up too heavily. Waves hitting the ice will also wash it overboard. Rime ice will form anywhere on the ship but, because the smaller droplets are carried by the wind, seems to be more prevalent on the upper structure. Rime ice can be expected to occur at any temperature in the icing range.

2. Glaze. Glaze ice, like its name implies, is characterized by its smooth, transparent appearance and high adhesive strength. Glaze ice will generally be found whenever there are large amounts of water either in the form of "green" water or large drops. The glazed appearance comes from the relatively slow freezing of the large supercooled droplet which spreads after impact and combines with the other drops to give a smooth, clear sheet. The large drops come chiefly from the spray generated by the vessel's passage through the water but heavy seas and high winds can produce the same situation. The high adhesive strength comes from the fact that when the droplet freezes on the structure, the water expands into the pores of the surface material and creates large mechanical forces (Reference 16). This aspect makes glaze ice the most dangerous form of icing on ships because the ice is very dense and difficult to remove by any means.

The locations most susceptible to glaze ice with respect to the engine intakes are inlet louvers that have been located outboard on the ship.

Glaze ice usually occurs when the air temperature is just below 0°C.

J. Intake Protection

The most important concept to keep in mind is that the intakes have to be sheltered as much as possible to eliminate the icing hazard. Since any icing that will occur will most likely come from spray, simply moving the inlets as far away as possible from the source of the spray could cut down the amount of water impinging on the inlet by an estimated 75%. Doing this could negate the need for anti-icing systems as suggested in Reference 7 with their associated expense and development time.

Another method of reducing spray on the inlets is suggested in Reference 5. This entails positioning the inlets facing inboard opposite each other abaft of a portion of superstructure or facing aft just forward of the superstructure.

No matter where the inlet is positioned, the system should incorporate some type of alternate air source which bypasses the demister. The simplest means of accomplishing this would be through the use of blow-in doors. These blow-in doors must have de-icing or anti-icing

capability to prevent ice buildup that would hinder their operation. This capability could be provided by heating strips around the door's edges. Since icing generally occurs during foul weather when a ship would need full engine power to maintain steerage way, the alternate air source has to be capable of handling the engine's maximum airflow. The actuation of the blow-in doors can be either automatic through a pressure drop sensor, or manual by a warning given to the ship's crew to open the doors.

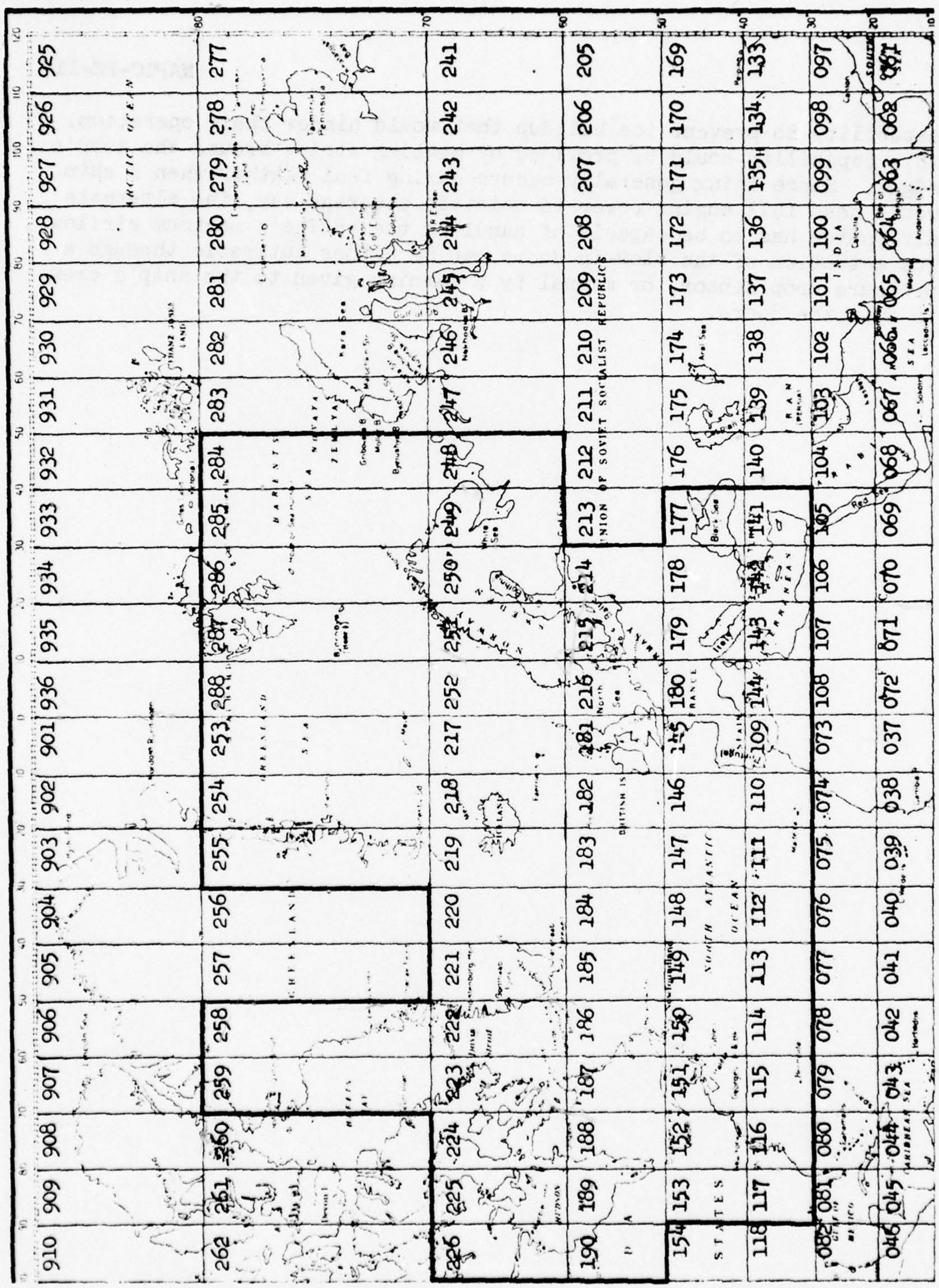
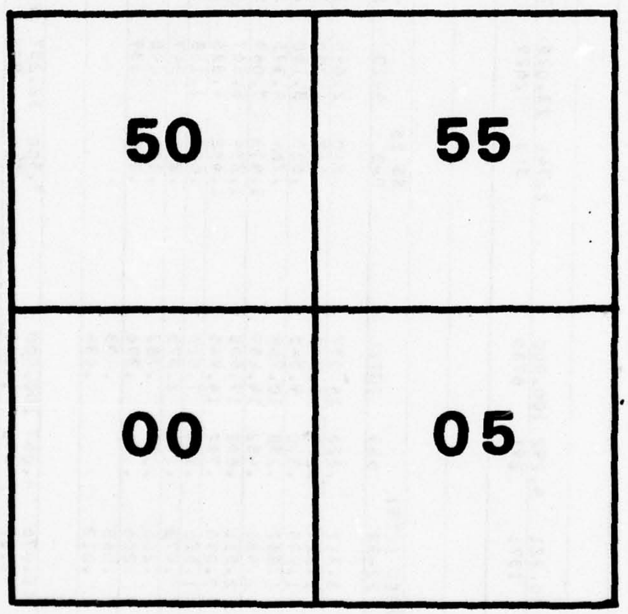


FIGURE 1: AREA COVERAGE OF NWSD STUDY

FIGURE 2: MARSDEN SUB-SQUARE NUMBERING SYSTEM



NOTE: Sub-square 00 is always oriented so it is closest to Equator and Prime Meridian, and sub-square 55 is furthest from the Equator and Prime Meridian.

FIGURE 3: TYPICAL OUTPUT PAGE FOR BI-VARIATE DISTRIBUTION

MSQ 116	SS 00			WIND SPEED (KTS)				SS 05		WIND SPEED (KTS)				MARCH
AIR TEMP	0-3	4-10	11-16	17-21	22-33	>33	TOTAL	0-3	4-10	11-16	17-21	22-33	>33	TOTAL
>15	3.215	20.103	21.298	14.292	13.215	2.434	74.558	2.128	18.191	21.072	16.351	14.398	2.049	74.190
14, 15	.457	2.552	2.699	2.507	2.935	.634	11.785	.254	2.154	2.417	1.857	2.146	.403	9.231
12, 13	.251	1.416	1.829	1.740	2.301	.782	8.319	.219	1.463	1.909	1.638	2.023	.552	7.803
10, 11	.029	.516	.826	.782	1.121	.206	3.481	.053	.666	.955	1.060	1.375	.403	4.510
8, 9	.044	.118	.221	.310	.487	.177	1.357	.044	.368	.464	.543	.797	.289	2.505
6, 7		.029	.029	.088	.118	.059	.324	.026	.166	.307	.272	.447	.116	1.331
4, 5	.015	.015	.015	.029	.029		.103	.009	.009	.079	.070	.105	.053	.324
2, 3		.015	.029	.015	.015		.074	.009	.009	.018	.018	.018	.026	.096
0, 1											.009			.009
-2, -1														
-4, -3														
-6, -5														
-8, -7														
-10, -9														
< -10														
TOTAL %	4.012	24.764	26.947	19.764	20.221	4.292	100.000	2.741	23.025	27.220	21.816	21.308	3.889	100.000
TOTAL OBS	272	1679	1827	1340	1371	291	6780	313	2629	3108	2491	2433	444	11418

MSQ 116	SS 50			WIND SPEED (KTS)				SS 55		WIND SPEED (KTS)				MARCH
AIR TEMP	0-3	4-10	11-16	17-21	22-33	>33	TOTAL	0-3	4-10	11-16	17-21	22-33	>33	TOTAL
>15	.413	3.190	3.405	2.932	3.311	.826	14.077	.210	2.048	1.528	1.666	1.771	.242	7.465
14, 15	.241	1.771	1.608	1.083	1.324	.275	6.303	.347	1.250	1.250	.868	1.007	.104	4.826
12, 13	.396	2.649	2.528	1.668	1.995	.310	9.545	.625	3.160	2.743	1.632	2.118	.104	10.382
10, 11	.525	3.001	3.036	2.287	1.857	.258	10.964	.764	4.375	3.507	2.153	1.979	.069	12.847
8, 9	.783	4.308	4.214	2.588	2.485	.482	14.659	1.493	7.049	6.042	3.611	2.222	.139	20.556
6, 7	1.238	5.297	5.013	3.276	2.511	.662	17.998	1.354	6.667	5.868	2.882	2.743	.313	19.826
4, 5	1.169	4.652	3.784	2.528	2.090	.722	14.945	1.458	4.826	2.674	1.771	1.701	.313	12.743
2, 3	.421	2.150	1.754	1.419	1.556	.318	7.619	.694	2.188	1.597	1.319	1.389	.313	7.500
0, 1	.120	.550	.585	.499	.473	.146	2.373	.243	.347	.451	.313	.417	.104	1.875
-2, -1	.086	.146	.138	.172	.206	.034	.783	.104	.208	.521	.382	.174	.035	1.424
-4, -3	.026	.043	.026	.060	.206	.034	.396	.208	.139	.069	.104	.035		.556
-6, -5		.017	.009	.034	.043		.103							
-8, -7		.009		.009	.017		.034							
-10, -9														
< -10														
TOTAL %	5.417	27.784	26.099	18.557	18.076	4.067	100.000	7.500	32.257	26.250	16.701	15.556	1.736	100.000
TOTAL OBS	630	3231	3035	2158	2102	473	11629	216	929	756	481	448	50	2880

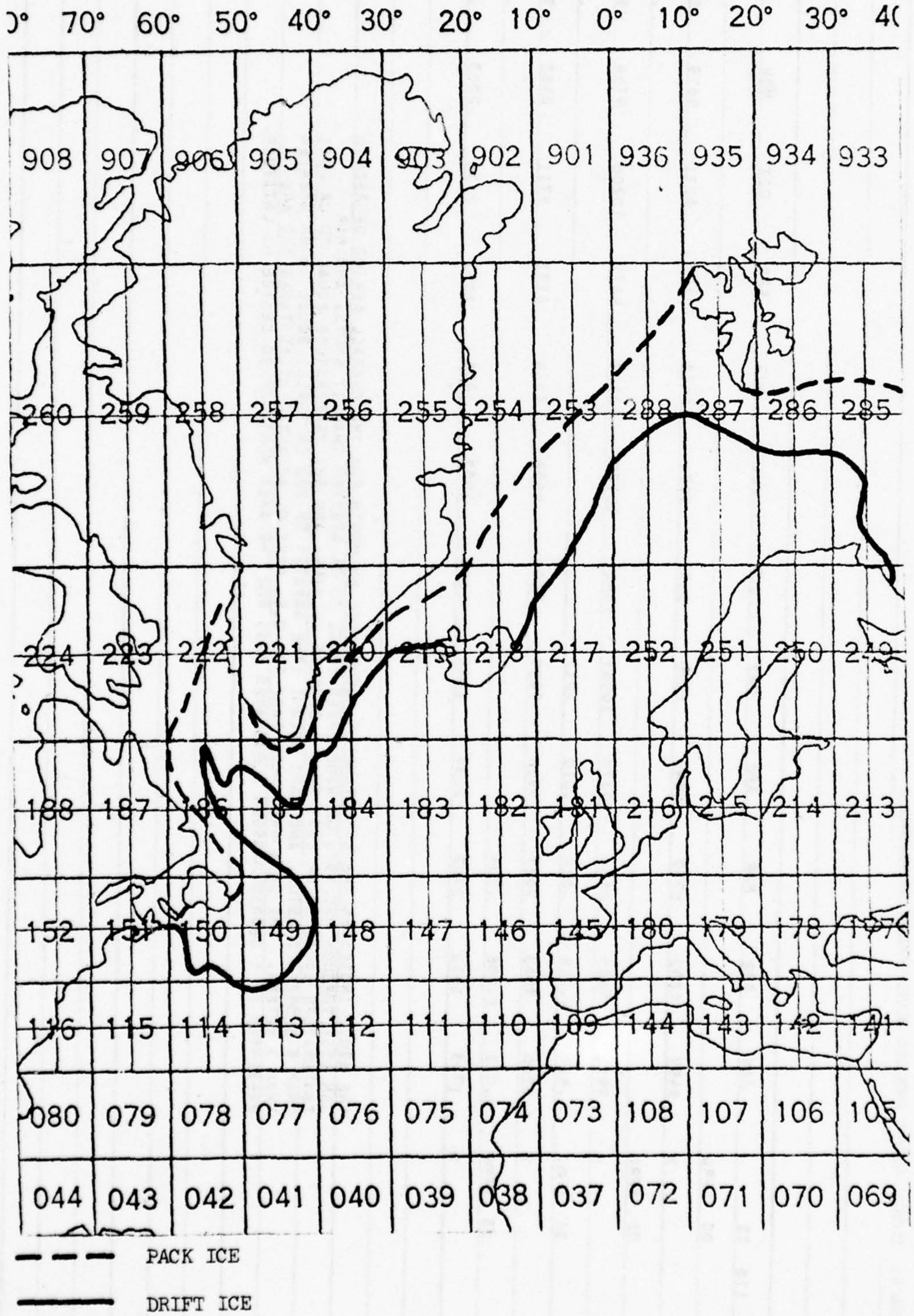
THESE TABLES SHOW THE BIVARIATE DISTRIBUTION OF THE OCCURRENCE OF WIND SPEED VS TEMPERATURE IN DEGREES CELSIUS. THE TABLES ARE POR MONTH COVERING THE PERIOD JAN 1961 THROUGH DEC 1970. THE DATA ARE TAKEN FROM THE U.S. NAVY N. ATLANTIC ATLAS TAPES AND ARE PRESENTED BY 5 DEGREE MARSDEN SUBSQUARES (SS) FOR THE AREA NORTH OF 30 DEGREE N. LATITUDE. TABULAR VALUES ARE PERCENTAGE FREQUENCIES.

FIGURE 4: TYPICAL OUTPUT PAGE FOR MULTI-VARIATE DISTRIBUTION

MSQ 116	SS		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	00	%FRQ												
		N	5499	4892	5989	5899	5799	5399	5674	5488	5453	6031	5679	5050
	05	%FRQ												.011
		N	9911	9065	10546	10278	10069	10411	10129	10203	9672	10200	9704	9001
	50	%FRQ	1.414	2.219	.519	.010	.011							.013
		N	8206	8563	9627	9924	9239	7800	8458	8624	8131	8711	8385	7521
	55	%FRQ	4.011	2.206	.304									.210
		N	1745	1813	2303	2035	2044	2143	1957	1956	2091	2134	2003	1427

THE ABOVE INDICATES THE SIMULTANEOUS OCCURRENCE BY MONTH FOR THE OVERALL PERIOD OF RECORD JAN 1961 THROUGH DEC 1970 OF WIND SPEED EQUAL TO OR GREATER THAN 17 KNOTS, AND AIR TEMPERATURE EQUAL TO OR LESS THAN 0 DEGREES CELSIUS, AND SEA TEMPERATURE EQUAL TO OR LESS THAN 5 DEGREES CELSIUS, AND WAVE HEIGHT (THE GREATER OF SEA OR SWELL) EQUAL TO OR GREATER THAN 3 METERS. THE DATA ARE TAKEN FROM THE U.S. NAVY N. ATLANTIC ATLAS TAPES AND ARE PRESENTED BY 5 DEGREE MARSDEN SUBSQUARES (SS) FOR THE AREA NORTH OF 30 DEGREE N. LATITUDE.

FIGURE 5: APPROXIMATE MAXIMUM EXTENT OF PACK AND DRIFT ICE



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APPENDIX A

NAVSEC LTR ON MARINE GAS TURBINE SEPARATOR AND ANTI-ICE PROGRAM

NAPTC-PE-114

NAVAL SHIP ENGINEERING CENTER
CENTER BUILDING
PRINCE GEORGE'S CENTER
HYATTSVILLE, MARYLAND 20782

IN REPLY REFER TO
6146/PFH
9413
Ser 468

16 SEP 1975

From: Commander, Naval Ship Engineering Center
To: Officer in Charge, Naval Ship Engineering Center, Philadelphia Division
Commanding Officer, Naval Air Propulsion Test Center, Trenton, NJ

Subj: Marine Gas Turbine Separator and Anti-Ice Program

Ref: (a) NAVSEC ltr 6146/PFH 9415 Ser 680 dtd 24 Oct 1974
(b) NAVSEC ltr 6146/PFH 9415 Ser 82 dtd 10 Mar 1975

Encl: (1) WTA 6146-2 Rev. B.

1. Enclosure (1) revises the task assignment, under the Marine Gas Turbine Inlet Separation program defined in reference (a) as modified by reference (b). The enclosure also defines the anti-ice system work required to support the overall Marine Gas Turbine Inlet System Program. It should be noted that this document is intended to appoint a single organization responsibility of each subtask, where two organizations are appointed to a task the first one is lead.

R. S. Carleton

RICHARD S. CARLETON
By direction

SHIP TYPE All	DESIGN PHASE	
TITLE Gas Turbine Inlet Separatorand Anti-Ice Systems Program	2. WTA NO. 6146-2	3. REV. B

4. NAVSEC shall comment to NAPTC within 2 weeks.

5. NAPTC is responsible for obtaining test specimens.

6. NAPTC shall install the test specimens in the test rig and conduct the tests per plan.

7. NAVSECPHILADIV shall monitor the tests, and suggest modifications to the test as dictated by results. Any major redirection should be cleared with NAVSEC.

8. NAPTC shall reduce and analyze the data, and report tests results within 4 weeks of test completion.

9. NAVSECPHILADIV shall analyze the data and comment on results to NAVSEC four weeks after completion of test.

10. NAPTC shall report test progress semiformally on a weekly basis. NAPTC shall report significant events as they happen.

Task C Develop Separator Element Handbook: NAVSEC will compile the existing data ...rious single stage separators to provide design information for multi-stage ...s to meet specific environmental requirements.

Task D Development of Anti-Ice Systems: The objective of this task is to define icing conditions and evaluate methods of releaving them. This task is not limited to separators only; inlet silencers and engine bellmouths must be considered as well.

1. NAVSEC will task NAPTC to investigate icing conditions and recommend methods of evaluating anti-ice systems.

2. NAPTC will investigate icing conditions and report the conditions gas turbine inlet systems must be protected against. The report shall list all data sources.

3. NAVSEC and NAVSECPHILADIV shall comment on the report generated in sub-task D-2.

4. NAPTC shall develop a test plan to evaluate various methods of releaving icing conditions. This plan shall list methods to be tested, conditions each method is to be tested for, instrumentation, data to be recorded, and data reduction methods.

5. NAVSEC & NAVSECPHILADIV shall comment on Test Plan.

6. NAPTC shall procure all test hardware and make all pretest preparations.

7. NAPTC shall conduct the test according to plan. All significant deviations from the test plan should be approved by NAVSEC.

APPENDIX B

NAPTC LTR ON MARINE GAS TURBINE ICING STUDY, INTERIM REPORT

NAPTC-PE-114

DEPARTMENT OF THE NAVY
NAVAL AIR PROPULSION TEST CENTER
TRENTON, NEW JERSEY 08628

IN REPLY REFER TO:
PE63:EWM:jas
3960
Ser E734

16 MAR 1976

From: Commanding Officer, Naval Air Propulsion Test Center
To: Commander, Naval Ship Engineering Center, Center Building, Prince George's Center, Hyattsville, MD 20782 (Mr. P. Hawkins/ NAVSEC Code 6146)

Subj: Marine Gas Turbine Icing Study, Interim Report; submission of

Ref: (a) NAVSEC Work Task Assignment (WTA) 6146-2 Rev. B of 16 Sep 1975

Encl: (1) Interim Report, Marine Gas Turbine Icing Study

1. As described by Task D of reference (a), the enclosed data are forwarded as an interim report of a Marine Gas Turbine Icing Study presently underway at the Naval Air Propulsion Test Center.

2. Subsequent to further analyses, formal conclusions, recommendations and test program requirements will be submitted in compliance with task requirements.

R. K. BRUMWELL
By direction

Copy to:
NAVSECPHILADIV (Code 6734)

PE63:EWM:jas
Ser E734

INTERIM REPORT
MARINE GAS TURBINE ICING

Available literature researched to date indicates that icing of MGT demisters will be caused chiefly by spray. This includes both ship and wind generated spray.

Icing due to supercooled fog, the most prevalent cause of aircraft icing, is relatively non-existent on ships. Supercooled fog over the ocean is confined to the areas north of 60°N latitude and south of 60°S latitude. The period most likely to have supercooled fog is from November to February, inclusive, with December having the highest probability. During this four-month period, supercooled fog can be expected to occur on approximately 14 to 18 non-consecutive days.[1] Inquiries made of U.S. Naval and private vessels, as well as of vessels operated by foreign nations that frequent this area, substantiate this observation.

Table 1 is a compilation of the hydrometeorological conditions conducive to icing from six of the reports reviewed. Taking the extremes of these gives the range of values within which icing will most likely occur. Heavy icing generally occurs with air temperatures between -1.0°C and -18.0°C, water temperatures close to 0°C and winds above 9 meters/sec. Air temperatures below -18.0°C will cause the spray droplets to freeze before striking the ship and they do not adhere to the structure.

Two types of ice are prevalent on ships -- rime and glaze. Rime ice is generally found higher on the structure of the ship. This is due primarily to the fact that they are formed by small supercooled droplets that are carried higher and freeze instantaneously on impact. Glaze ice will form where there are large amounts of water taken on board. This water may be in the form of large supercooled drops or coarse "green" water. Because of the relatively slow freezing of these large drops, they tend to spread while freezing and form large sheets of ice with more adhesive power. Higher air temperatures generally result in glaze ice but rime ice can occur at any temperature in the range.

Keeping the above in mind, it would seem that MGT demisters, if placed in a relatively protected area on the structure, would be exposed only to a rime type of ice. This would be due to the torturous route that the airflow would have to follow to reach the demister. This path would act as an inertial separator and only those smaller droplets that could negotiate the route would impact on the demister. Glaze ice, as well as rime ice, is more likely to occur on inlets that are located outboard on the structure where large droplets and gross sea water could impinge on the demister.

K. T. Swan
NAPTC/PE63

PE63:EWM:jas
Ser E734

TABLE 1
HYDROMETEOROLOGICAL CONDITIONS CONDUCIVE TO ICING

OAT	SEA TEMP	WIND	SEA *	REFERENCE #
-1.5°C to -17.7°C	Slightly > 0°C	> 9 m/sec	-	7
Lower Limit of -18°C	-	-	-	15
0°C to -25°C	8°C to -2°C	> 8 m/sec	-	10
-5.8°C to -12.7°C	2°C to -1.4°C	9 m/sec to 15.6 m/sec		1962 9
-1°C to -7.3°C	2.4°C to -0.4°C	9.7 m/sec to	-	1963
-1°C to -14°C	3°C to -1.8°C	> 9.3 m/sec	-	6
-2°C to -7°C	0°C to -2.5°C	> 4.4 m/sec	1.2 m to 2.4 m	4
-4°C to -14°C	2°C to -3°C	> 4.4 m/sec	0.30 m to 3.6 m	

*Wave height

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14. Gathman, S. G., et al, "Marine Fog Observations in the Arctic," Naval Research Laboratory Report 7693, 1974

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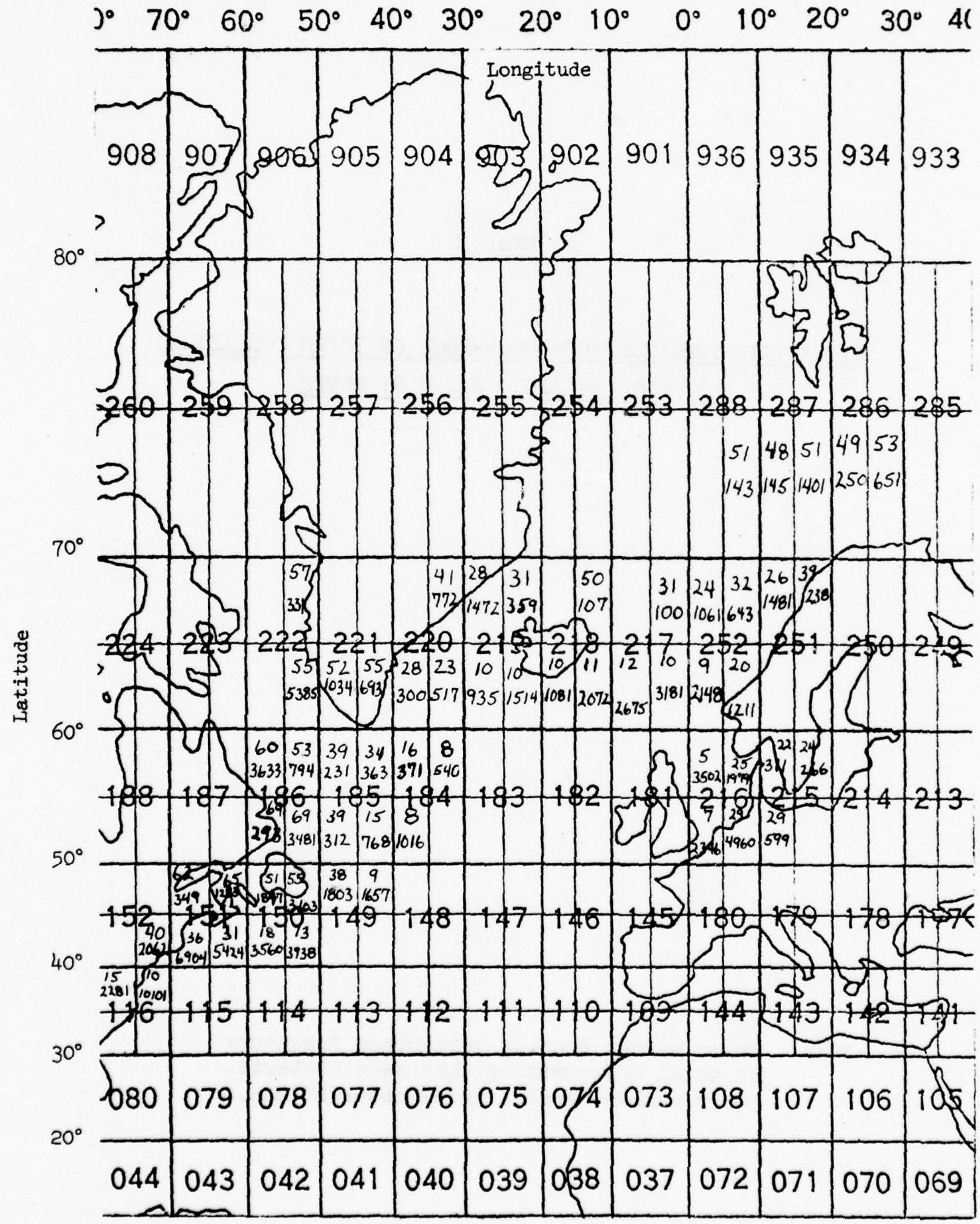
APPENDIX C

BI-VARIATE FREQUENCY-OF-OCCURRENCE OF ICING CONDITIONS FOR NORTH ATLANTIC BASIN BY MONTH

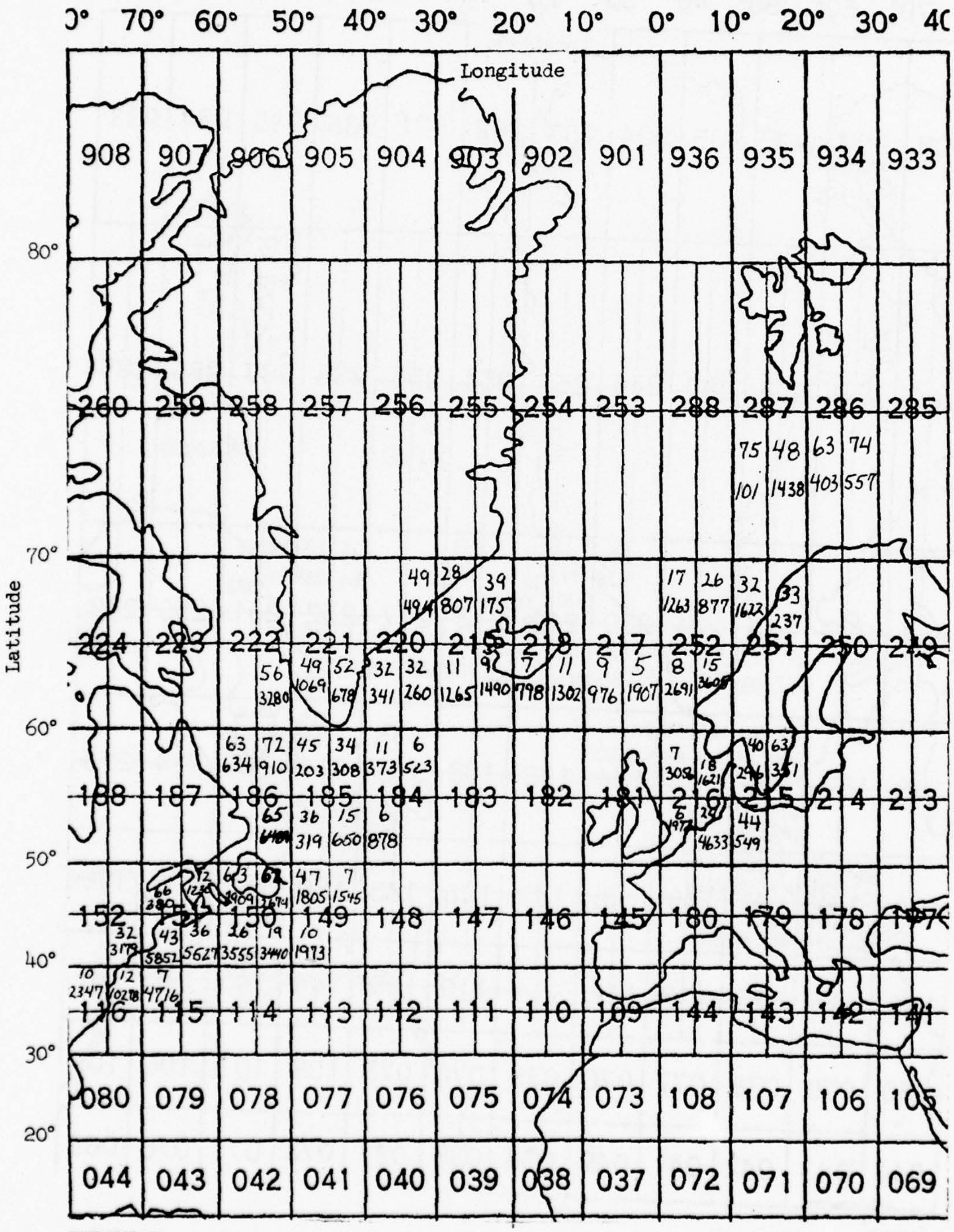
NOTE: Upper number denotes percentage frequency of total observations that meet criteria. Lower number denotes total observations.

FIGURE 1C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



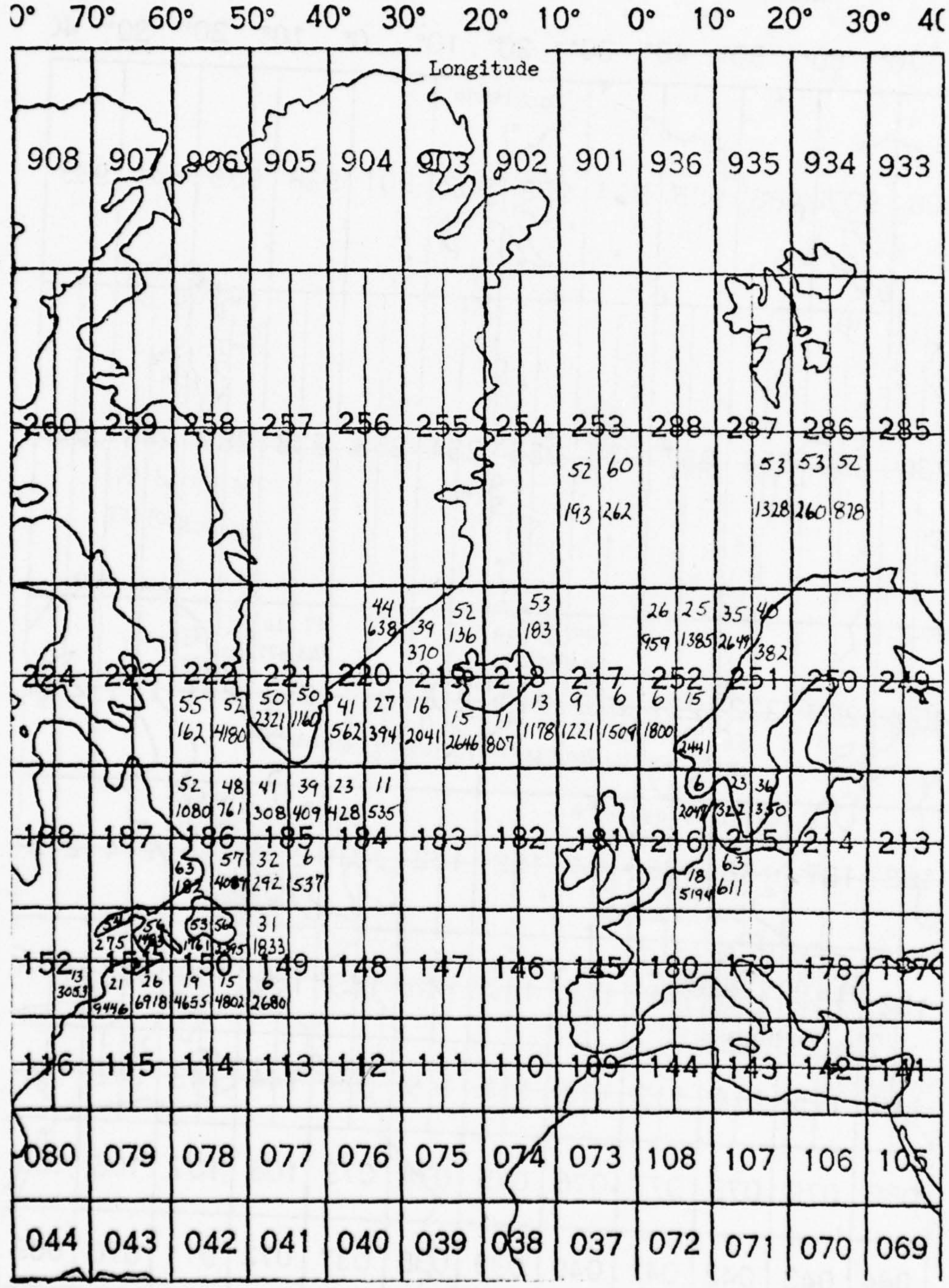
JANUARY

FIGURE 2C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



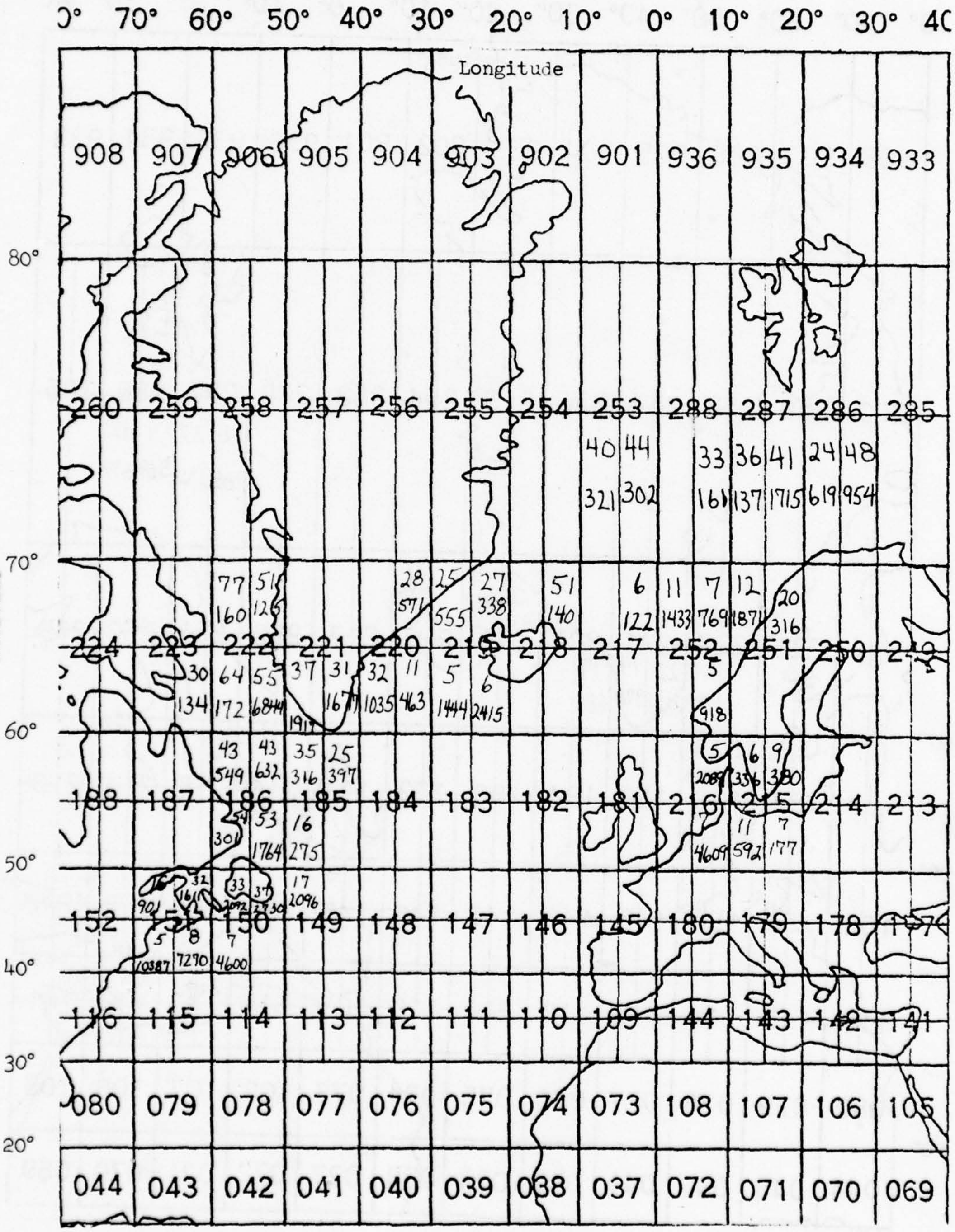
FEBRUARY

FIGURE 3C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



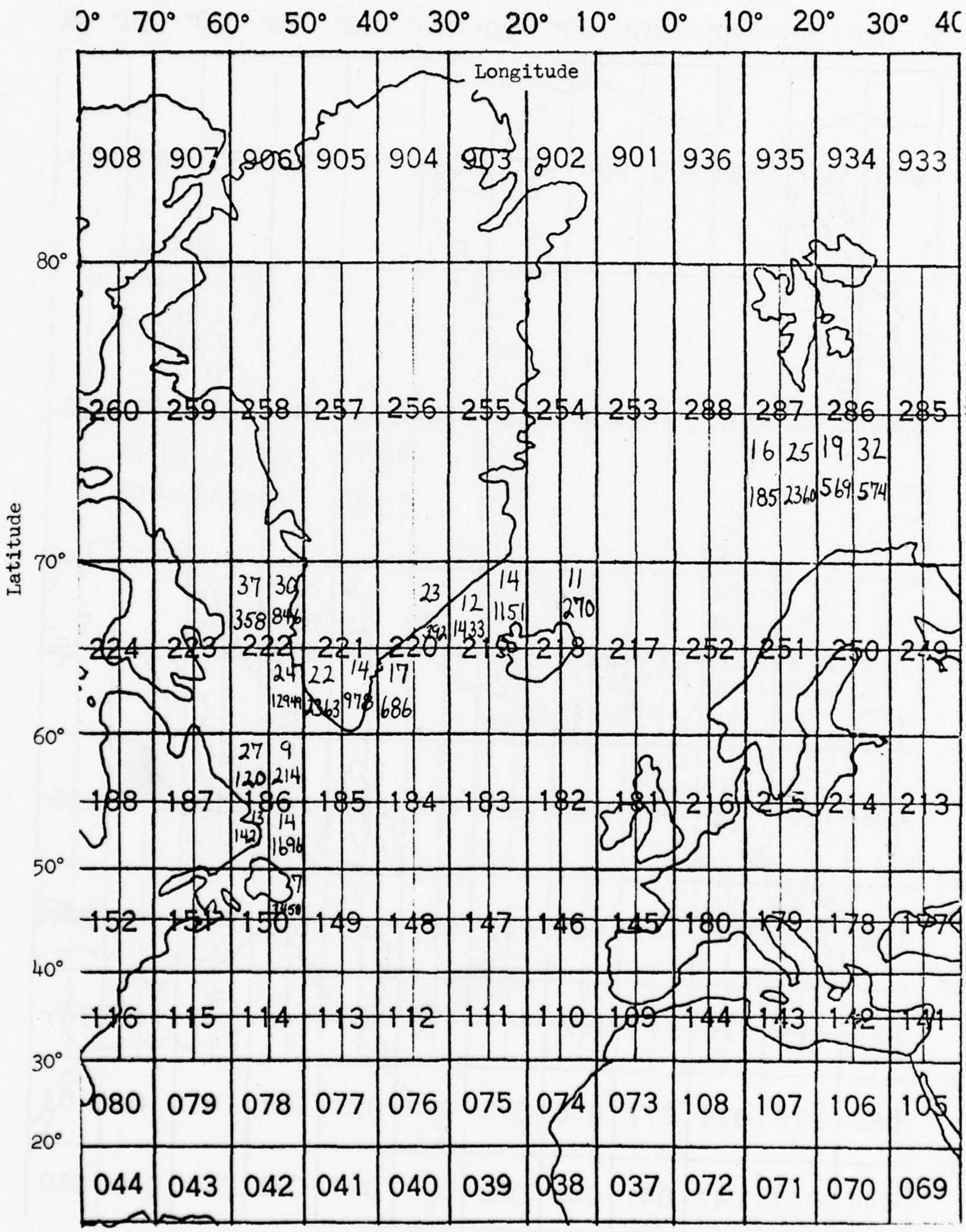
MARCH

FIGURE 4C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



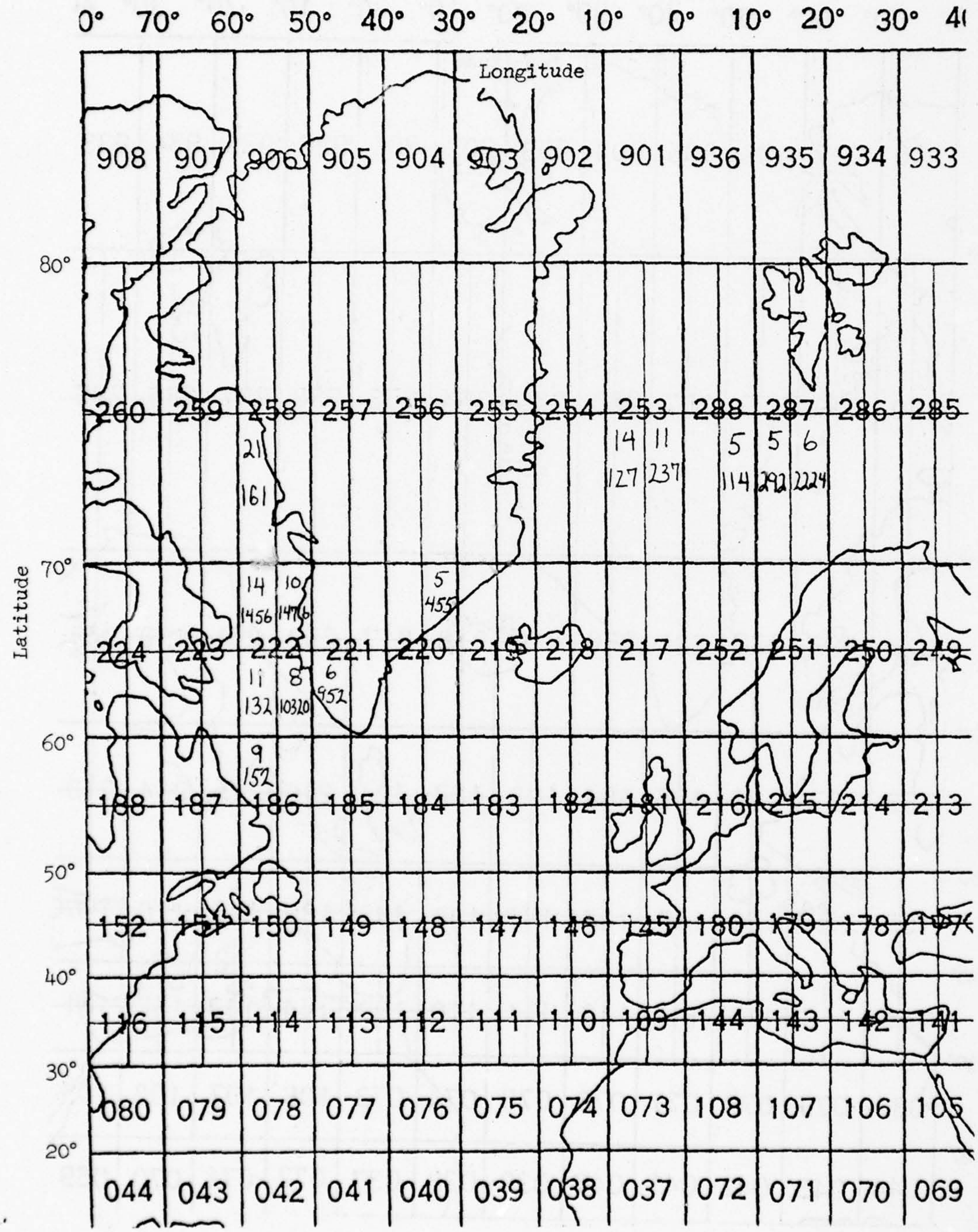
APRIL

FIGURE 5C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



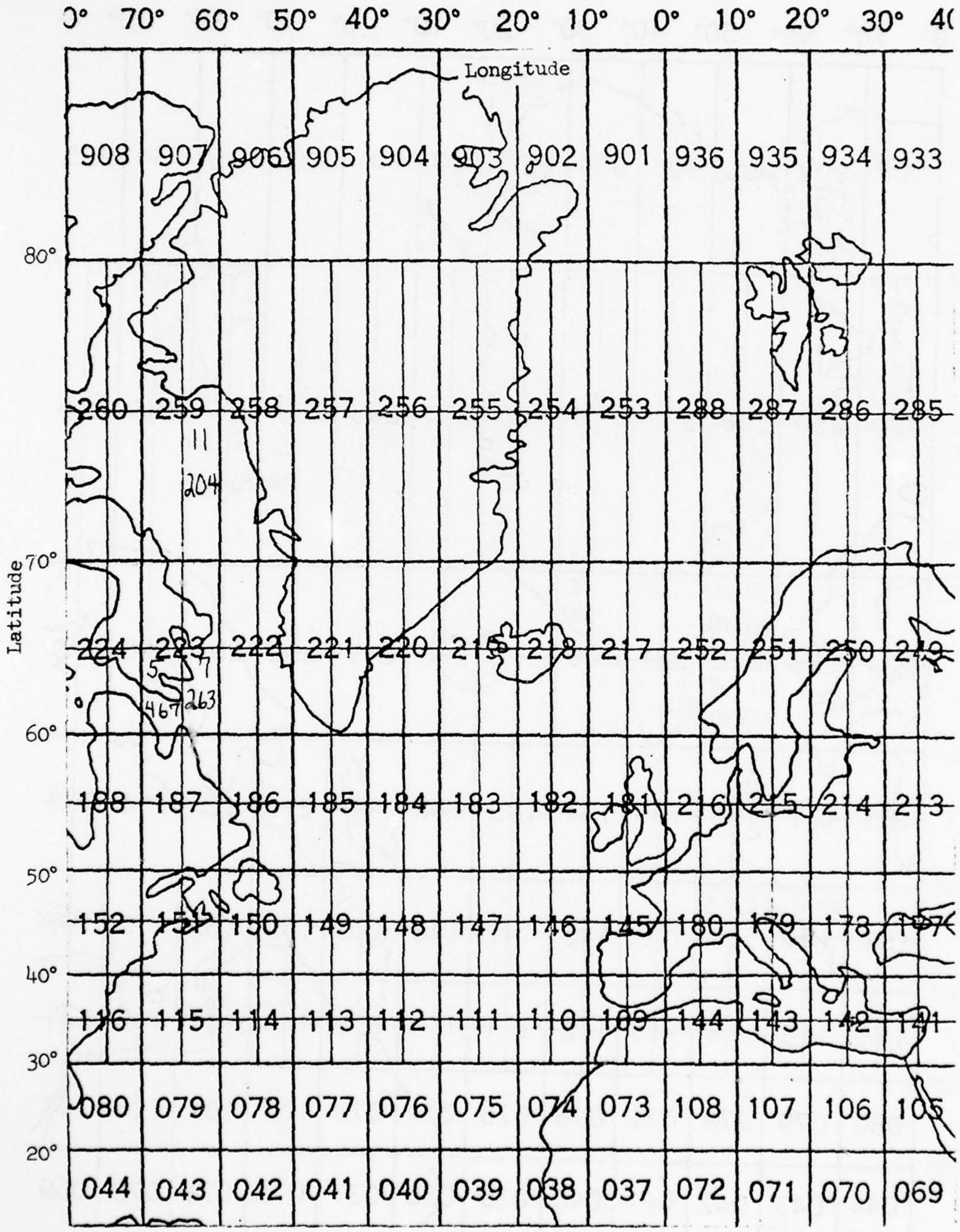
MAY

FIGURE 6C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



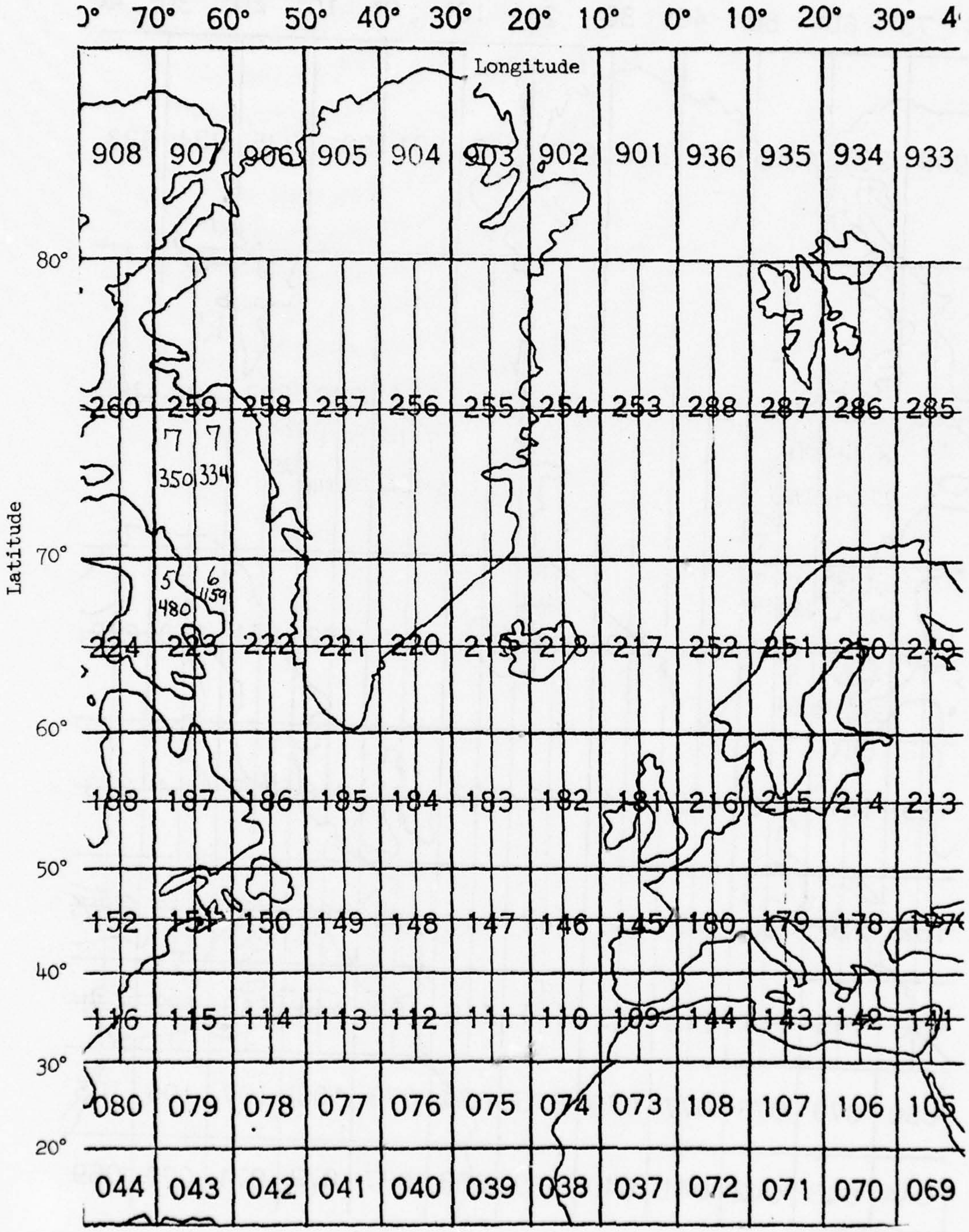
JUNE

FIGURE 7C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



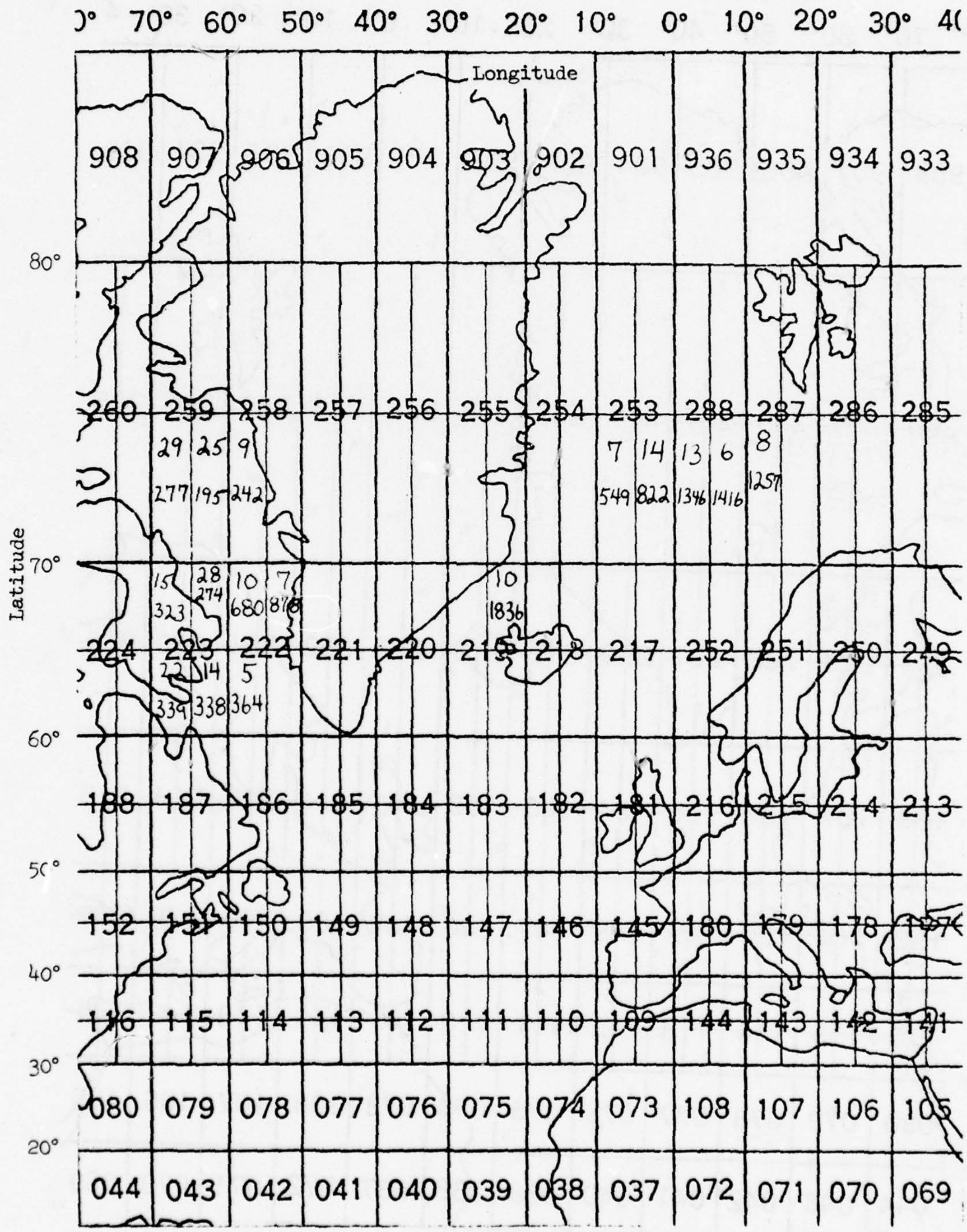
JULY

FIGURE 8C: Bi-Variate Frequency-of-Occurrence of Icing ____
Conditions for North Atlantic Basin



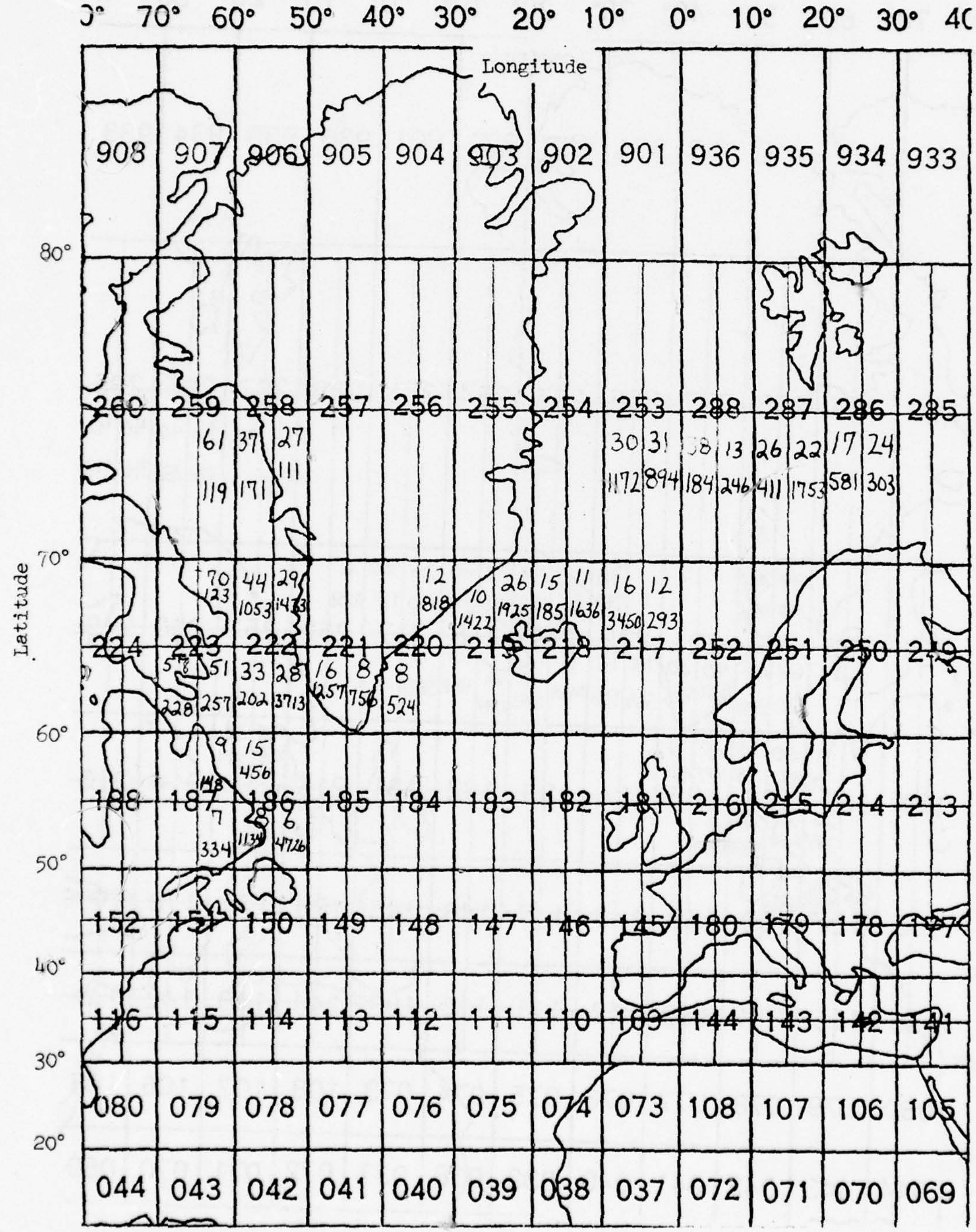
AUGUST

FIGURE 9C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



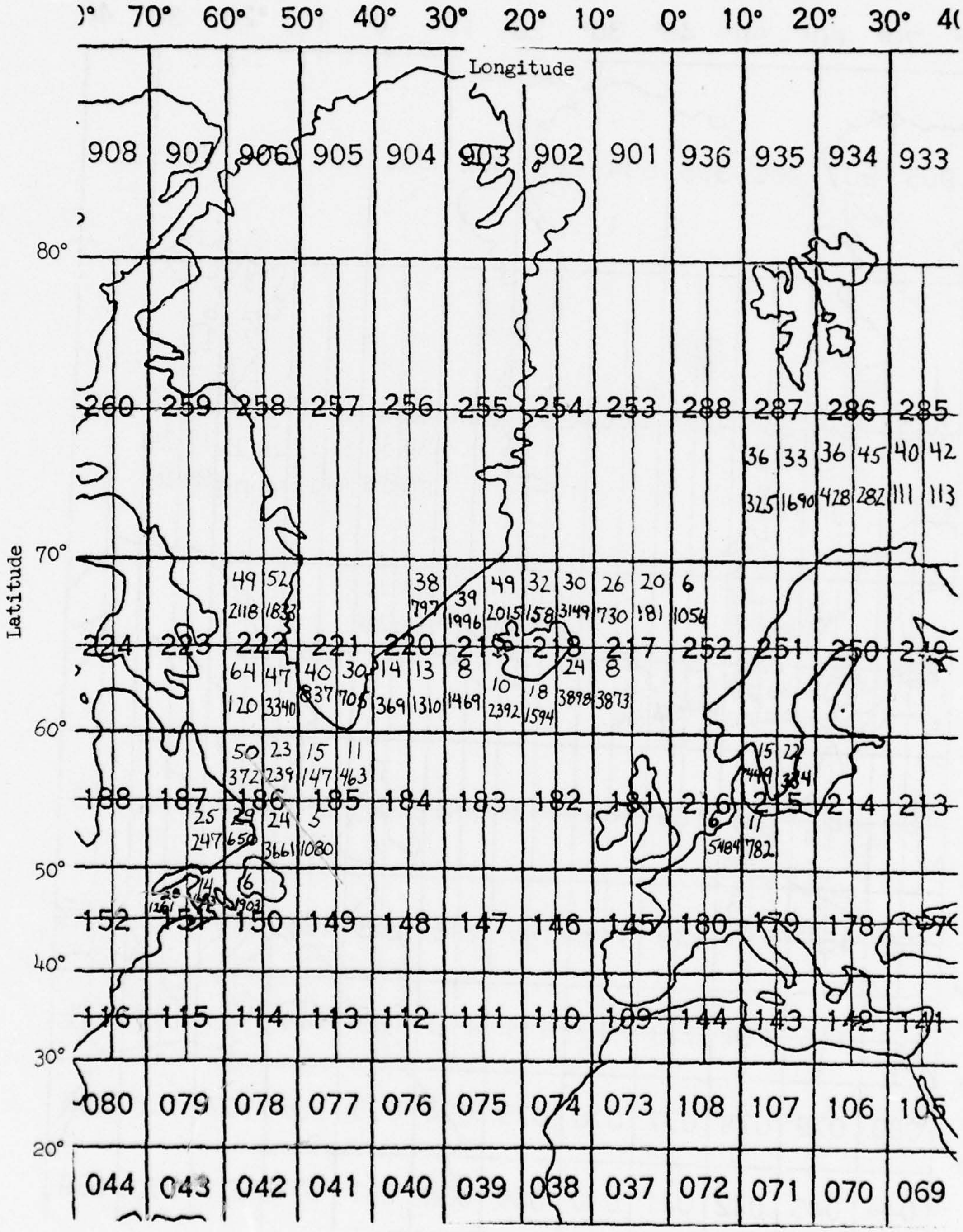
SEPTEMBER

FIGURE 10C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



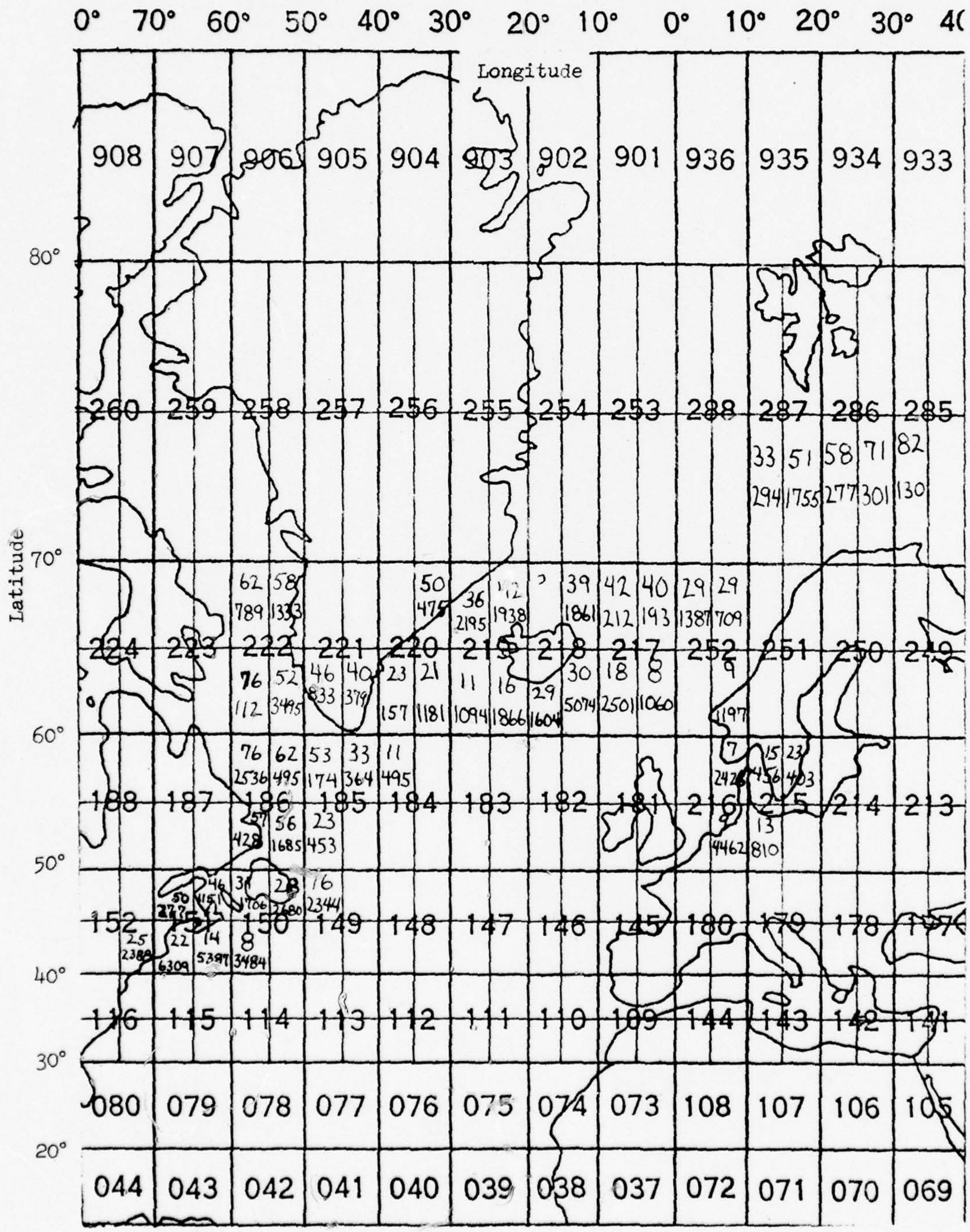
OCTOBER

FIGURE 11C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



NOVEMBER

FIGURE 12C: Bi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



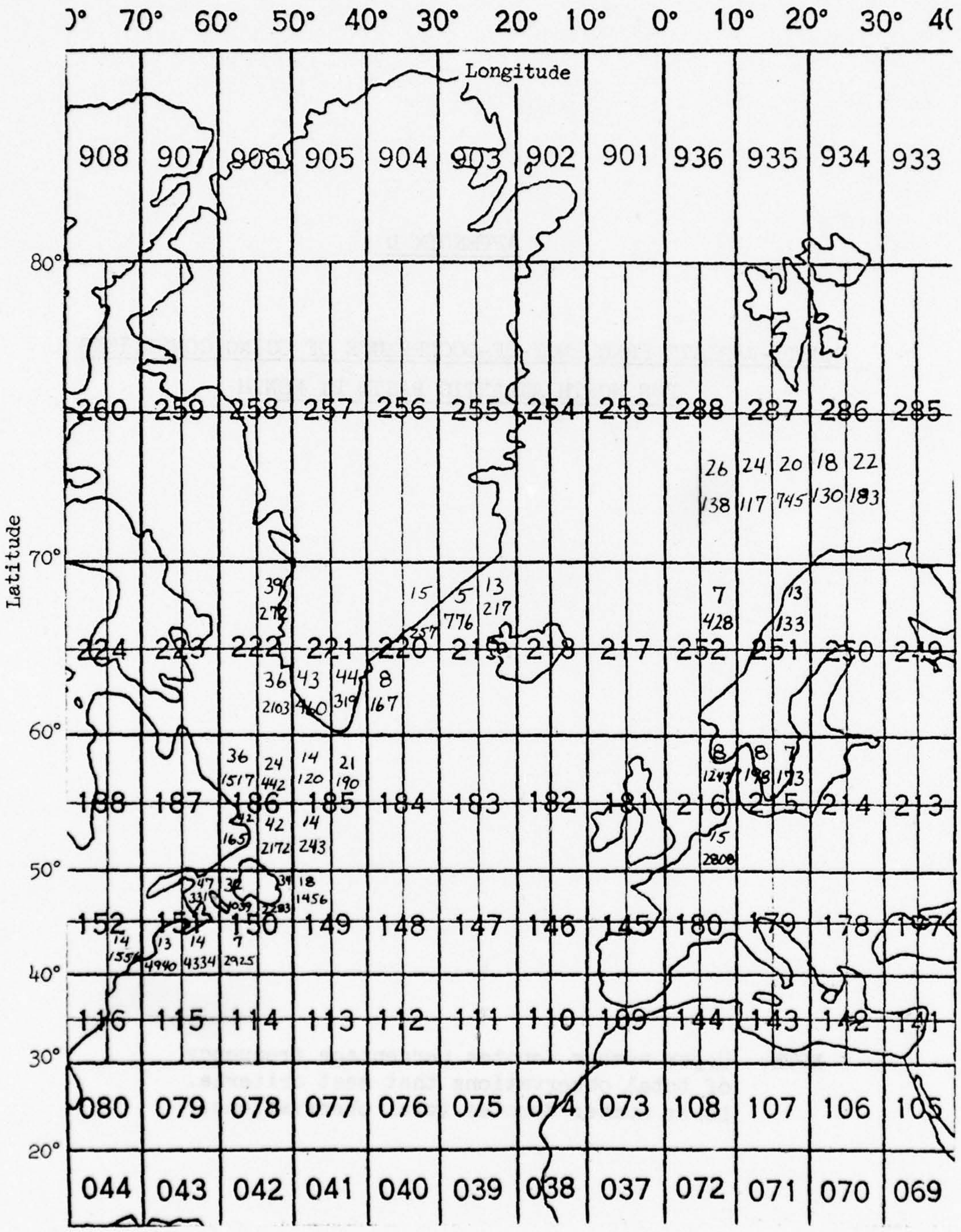
DECEMBER

APPENDIX D

MULTI-VARIATE FREQUENCY-OF-OCCURRENCE OF ICING CONDITIONS FOR NORTH ATLANTIC BASIN BY MONTH

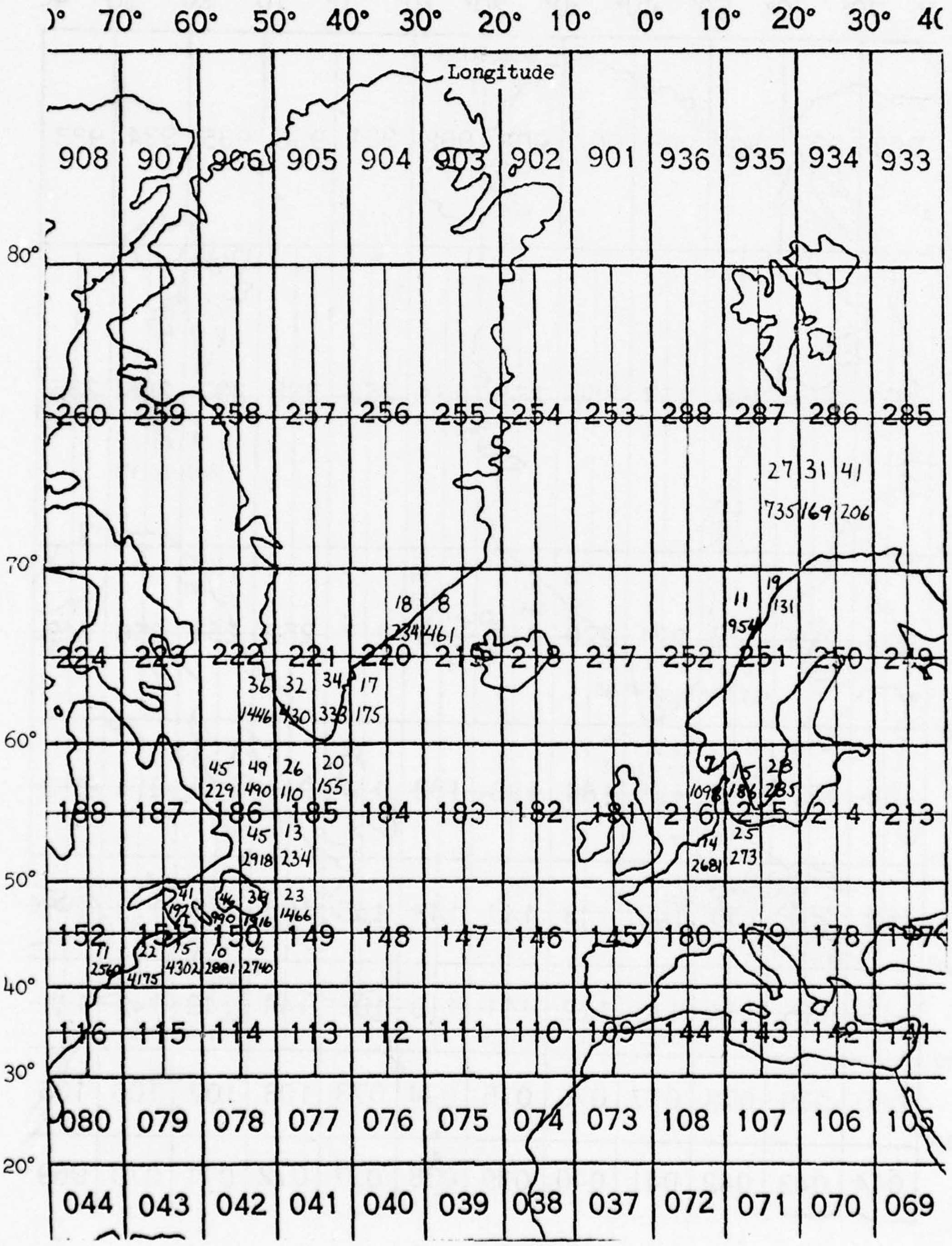
NOTE: Upper number denotes percentage frequency of total observations that meet criteria. Lower number denotes total observations.

FIGURE 1D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



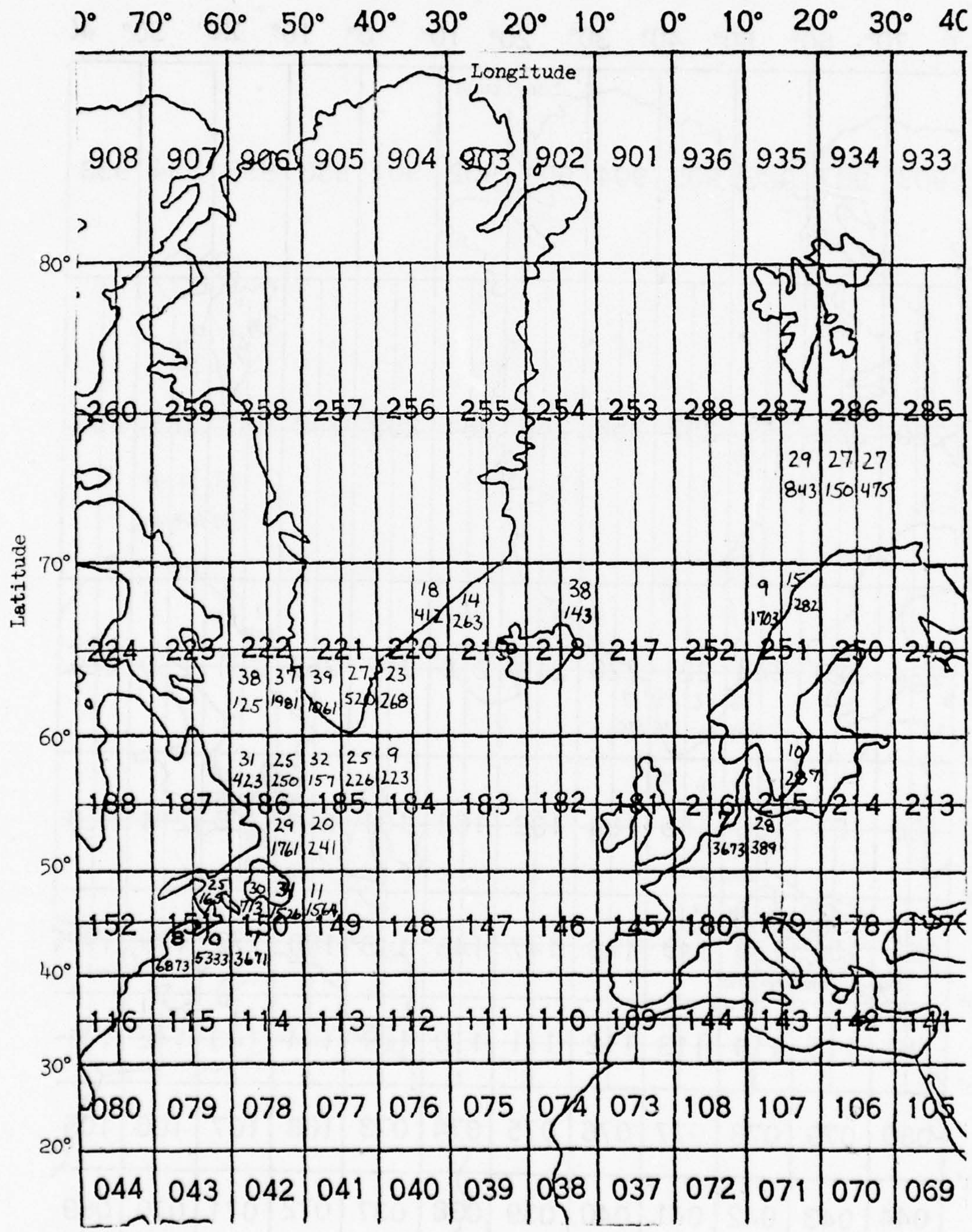
JANUARY

FIGURE 2D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



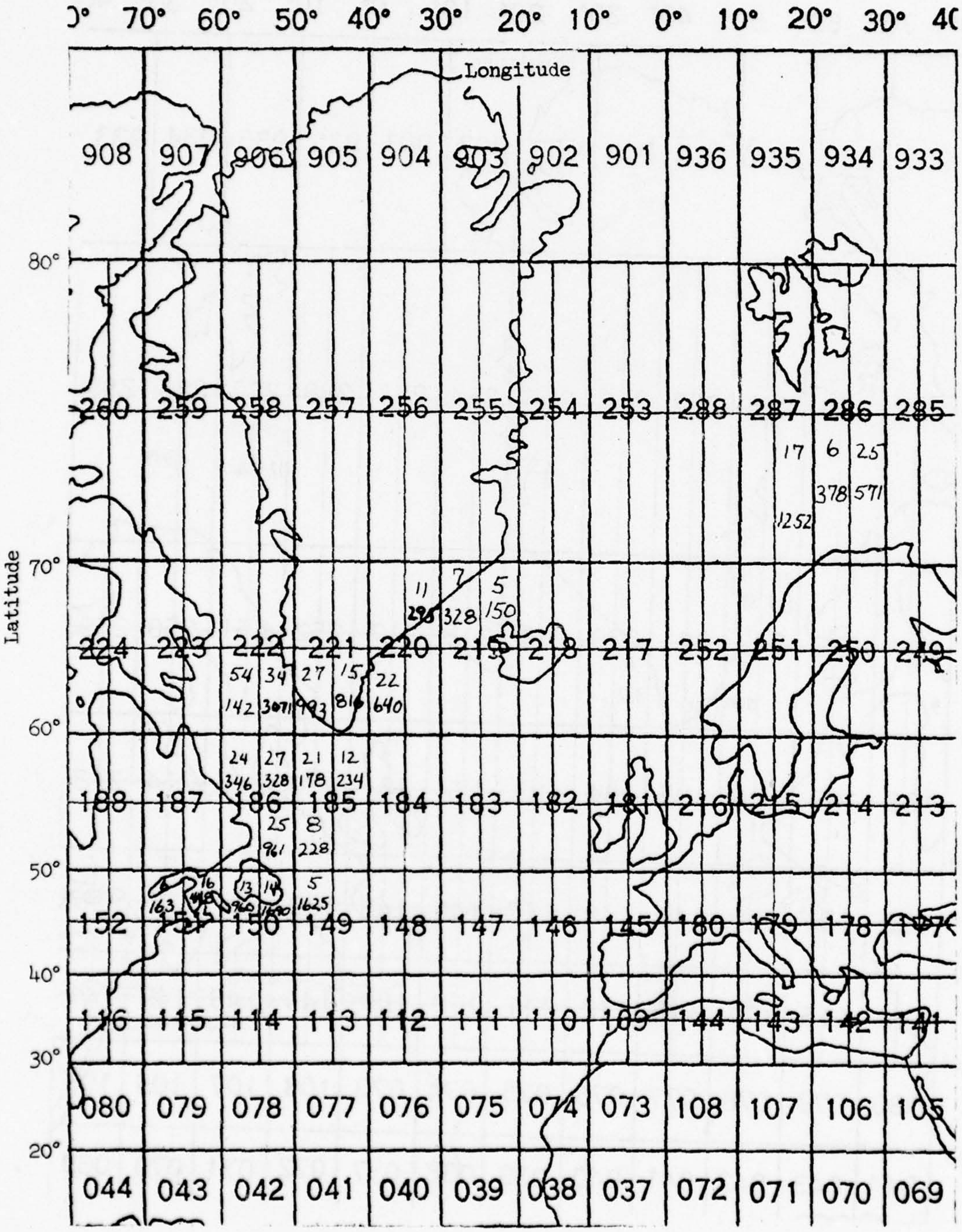
FEBRUARY

FIGURE 3D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



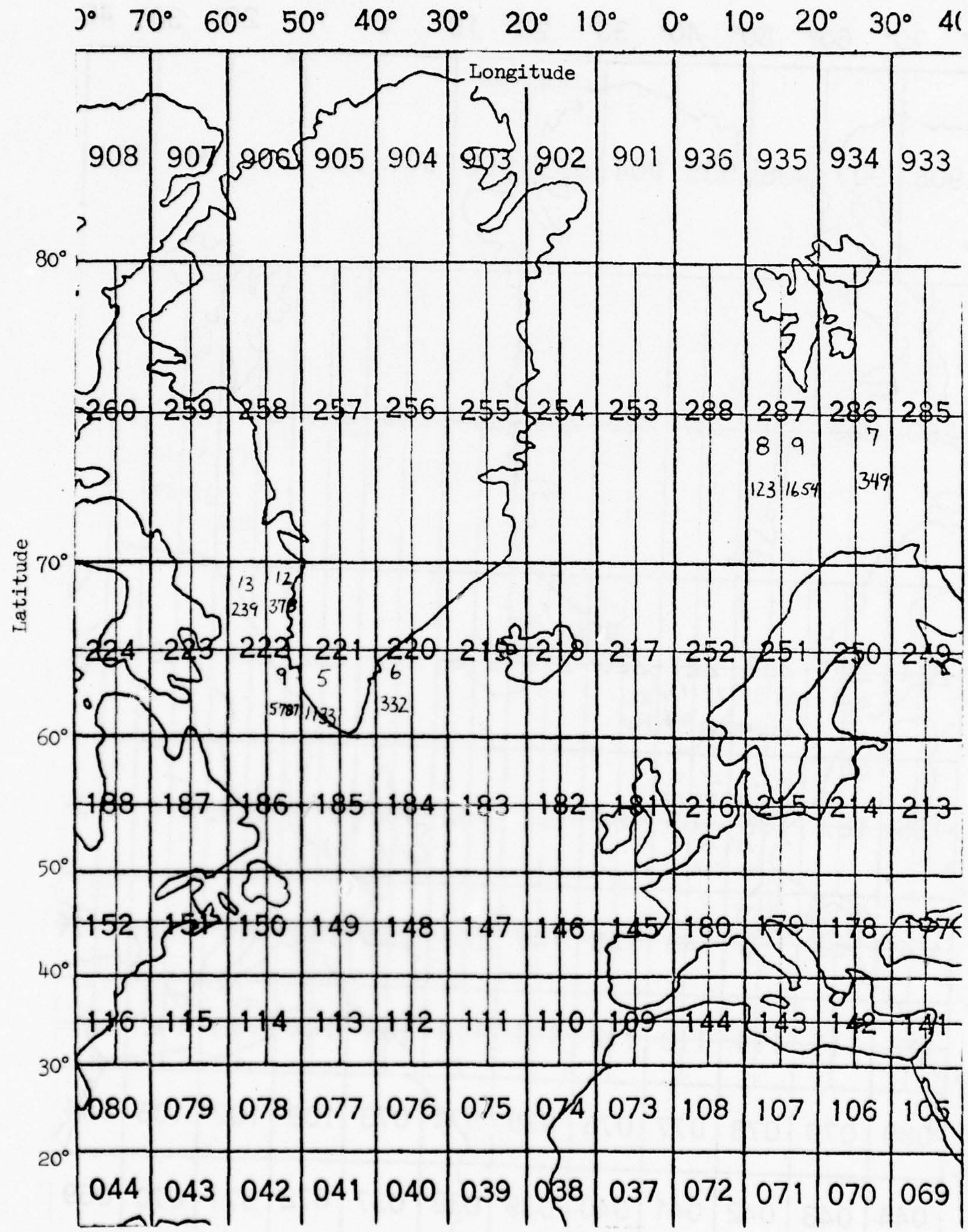
MARCH

FIGURE 4D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



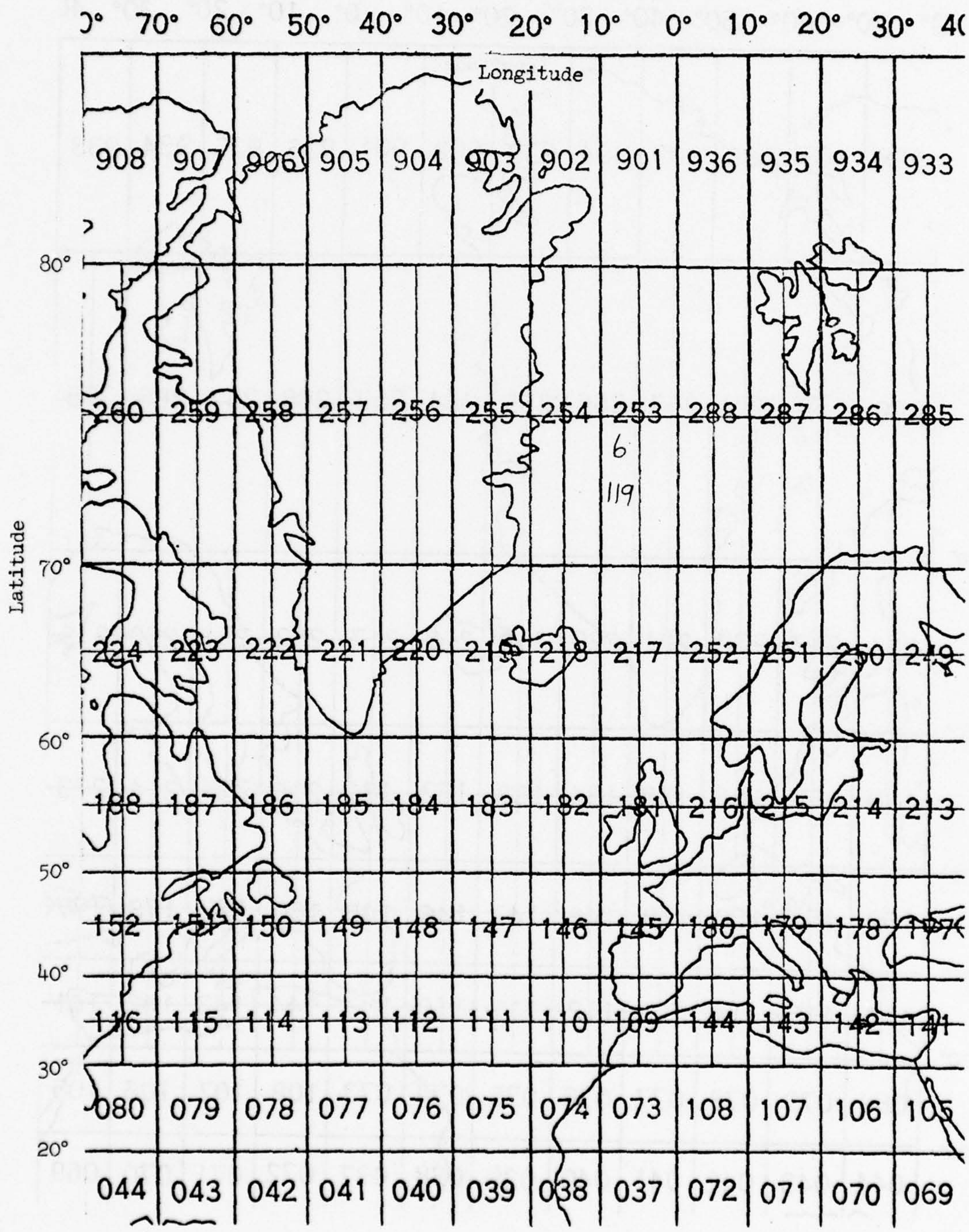
APRIL

FIGURE 5D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



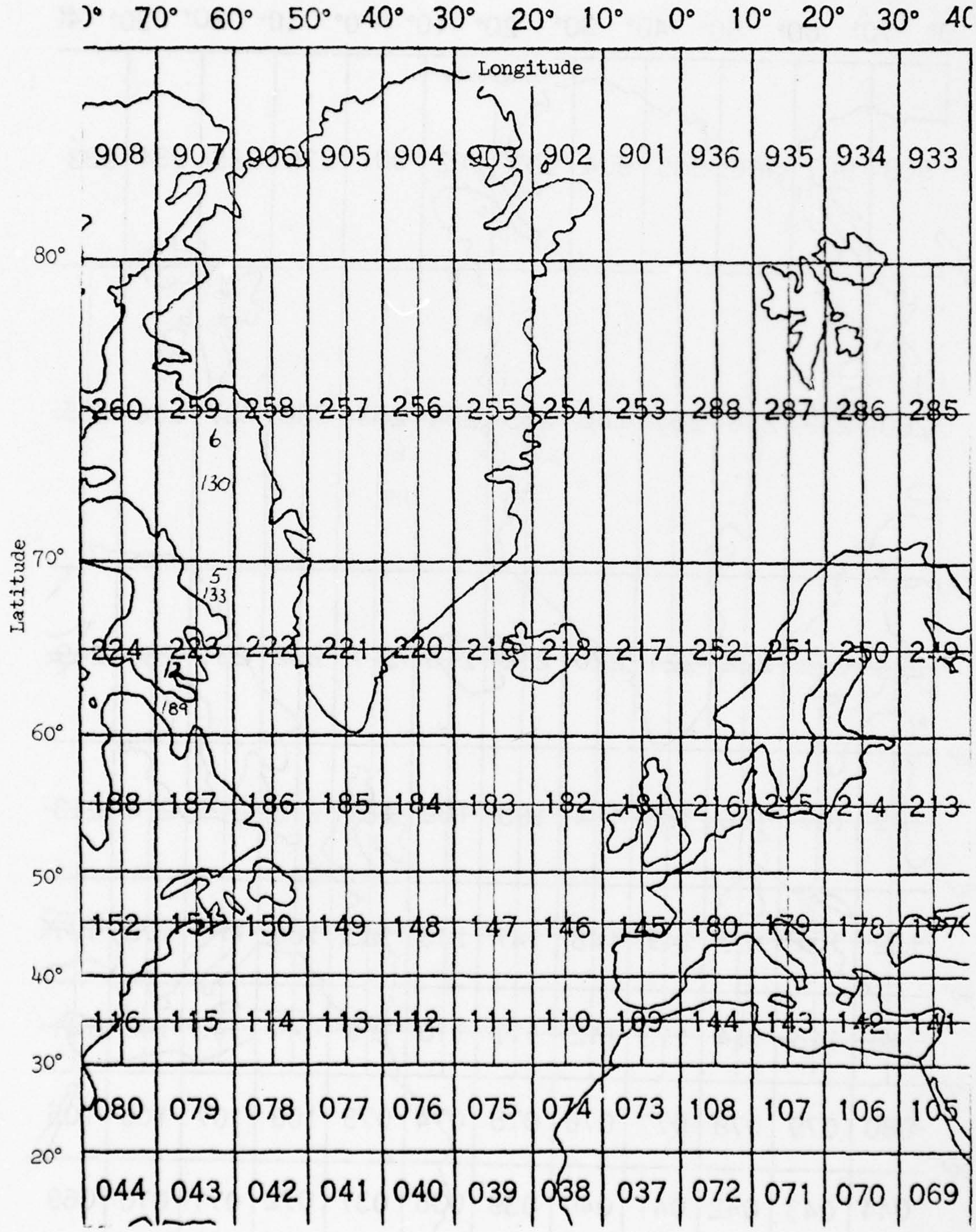
MAY

FIGURE 6D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



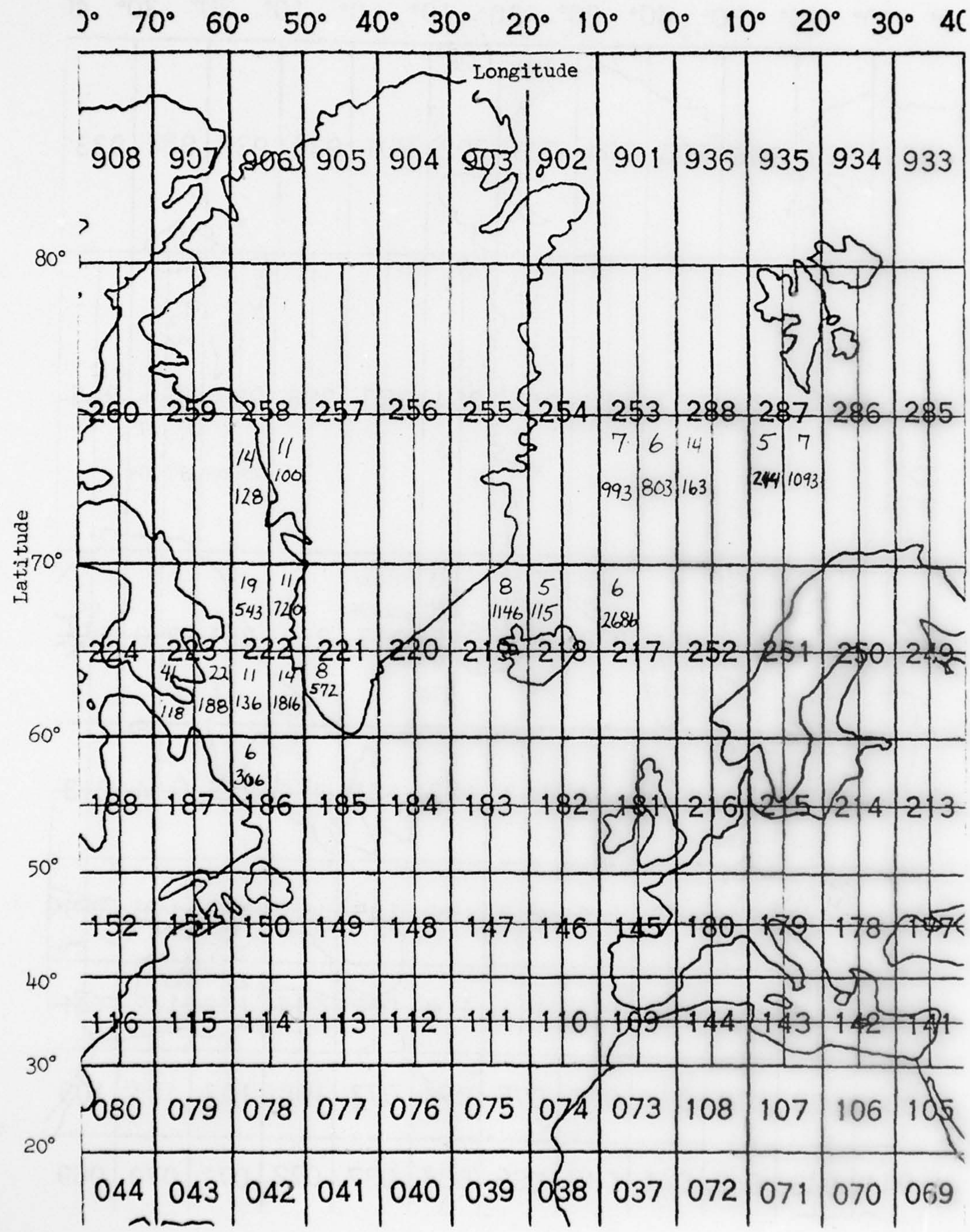
JUNE

FIGURE 7D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



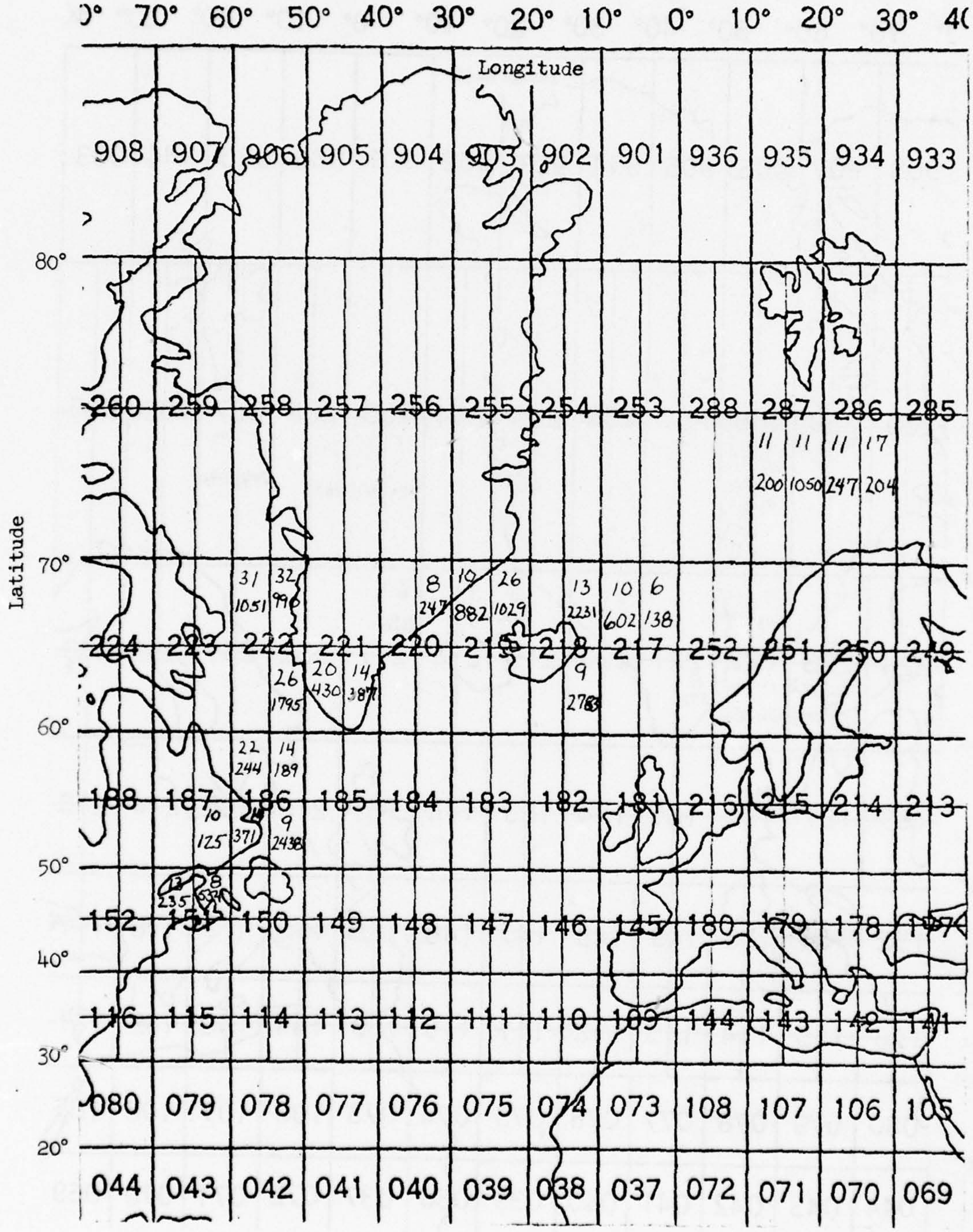
SEPTEMBER

FIGURE 8D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



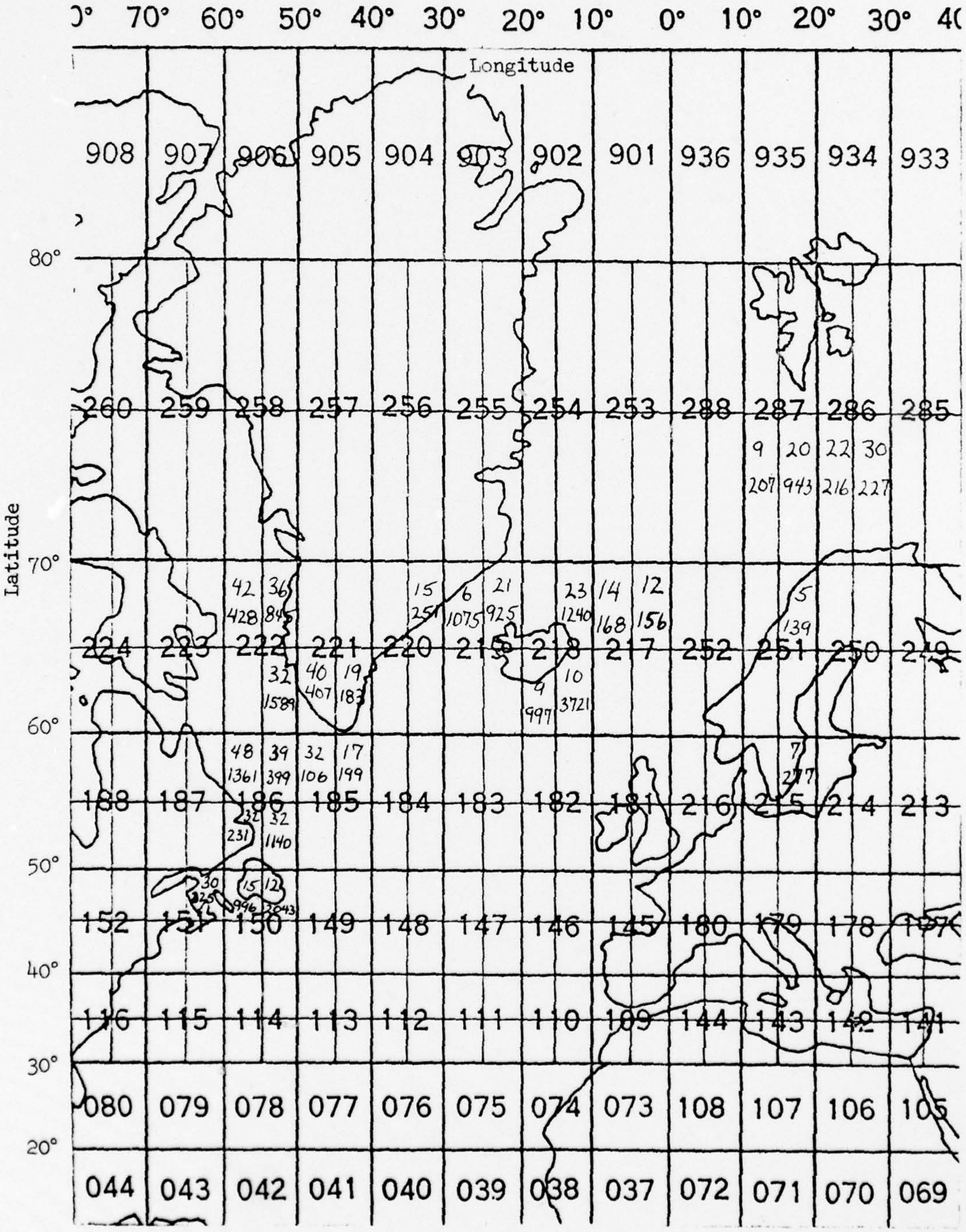
OCTOBER

FIGURE 9D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



NOVEMBER

FIGURE 10D: Multi-Variate Frequency-of-Occurrence of Icing Conditions for North Atlantic Basin



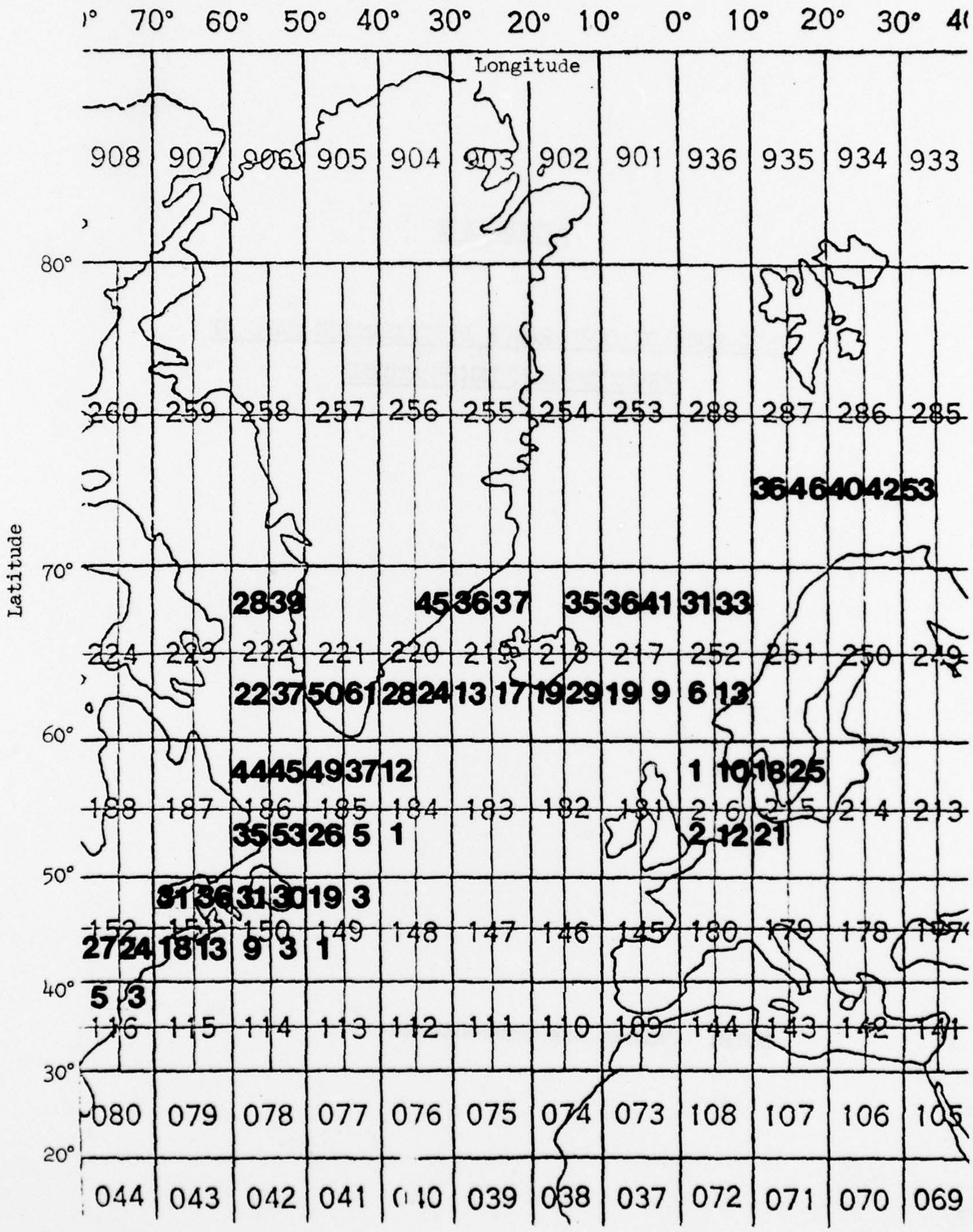
DECEMBER

APPENDIX E

FREQUENCY-OF-OCCURRENCE DISTRIBUTION MAPS OF FREEZING AIR TEMPERATURES

NOTE: Values are percentages.

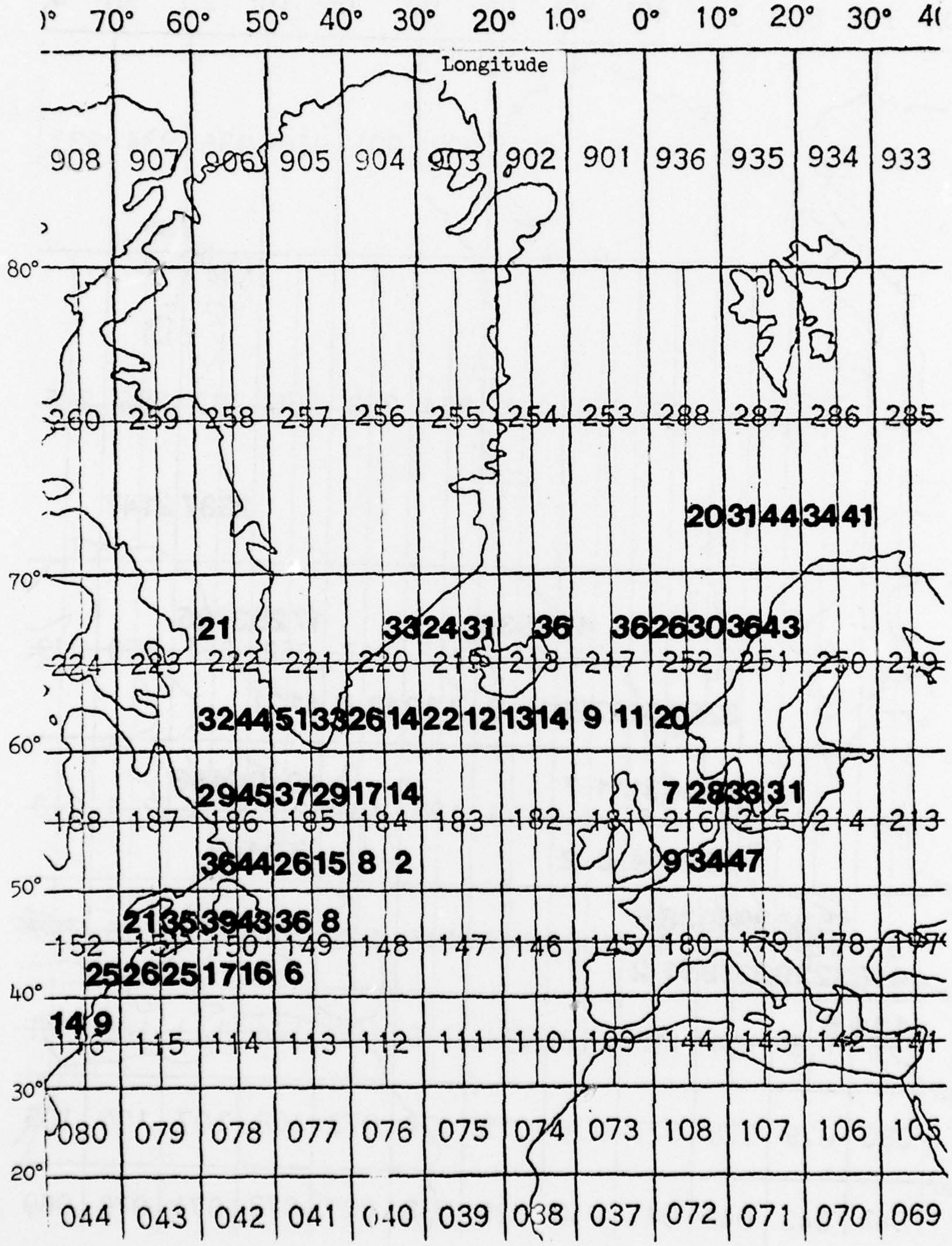
FIGURE 1E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



DECEMBER

Air Temp.: +1°C to -2°C

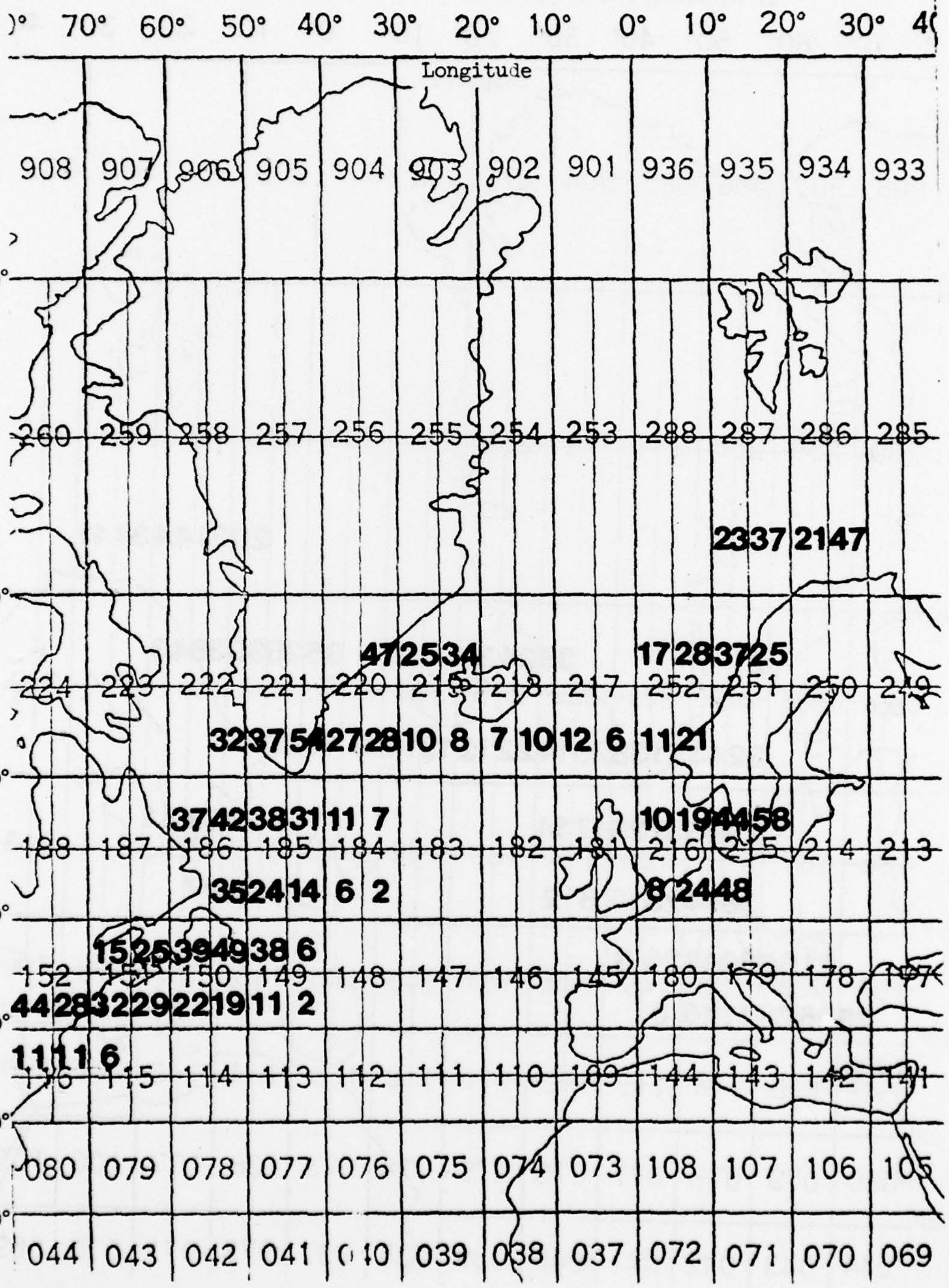
FIGURE 2E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



JANUARY

Air Temp.: +1°C to -2°C

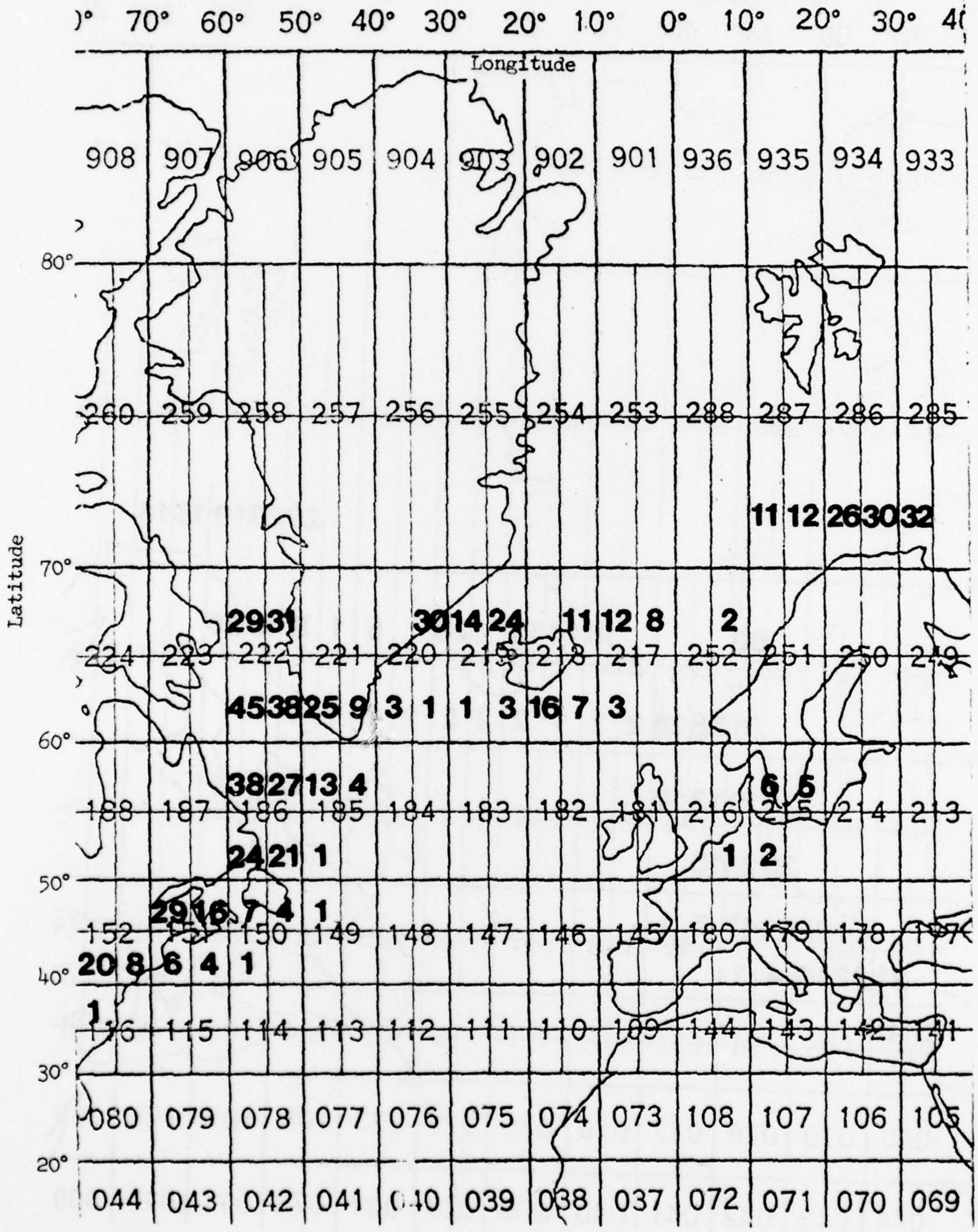
FIGURE 3E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



FEBRUARY

Air Temp.: +1°C to -2°C

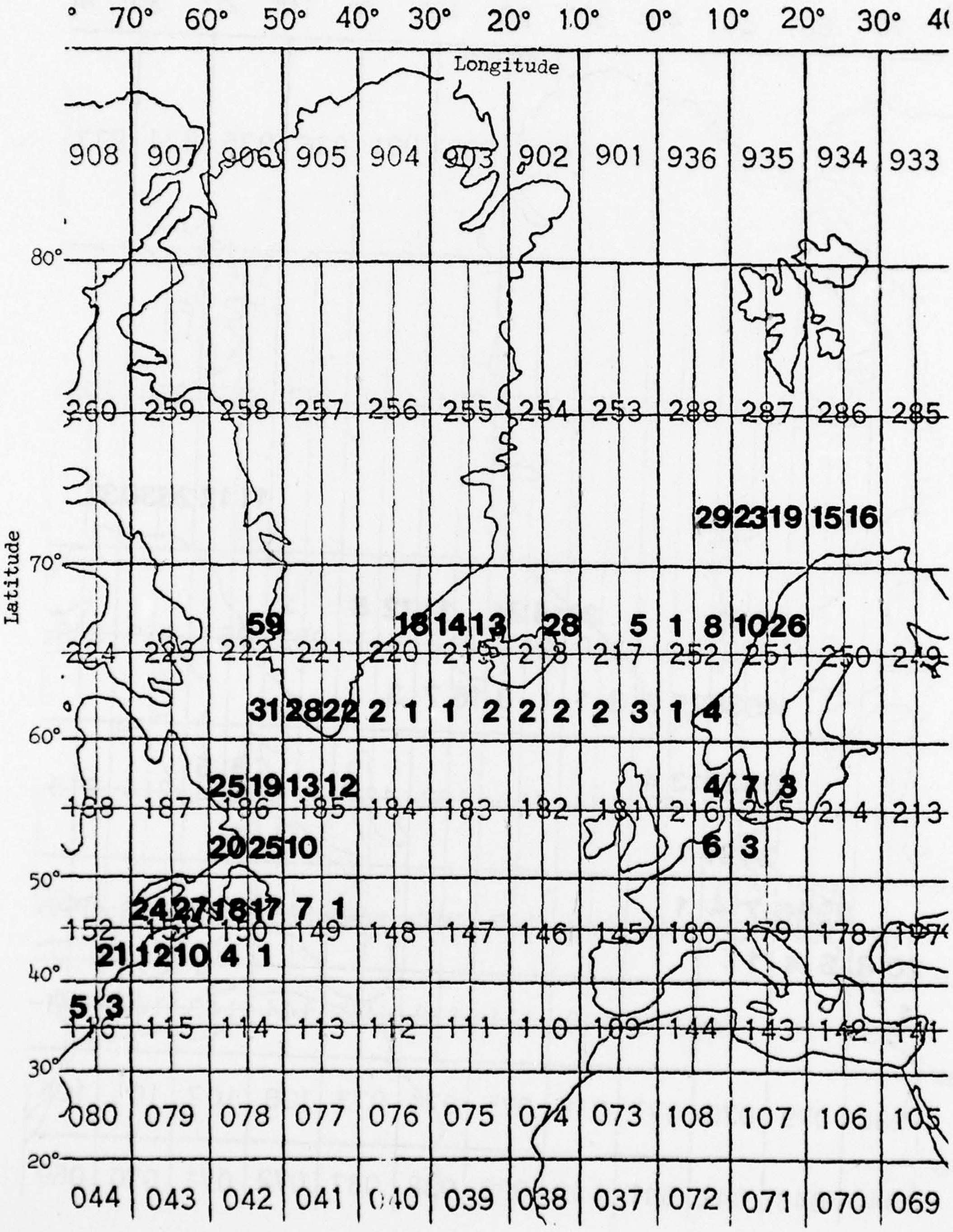
FIGURE 4E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



DECEMBER

Air Temp.: -3°C to -6°C

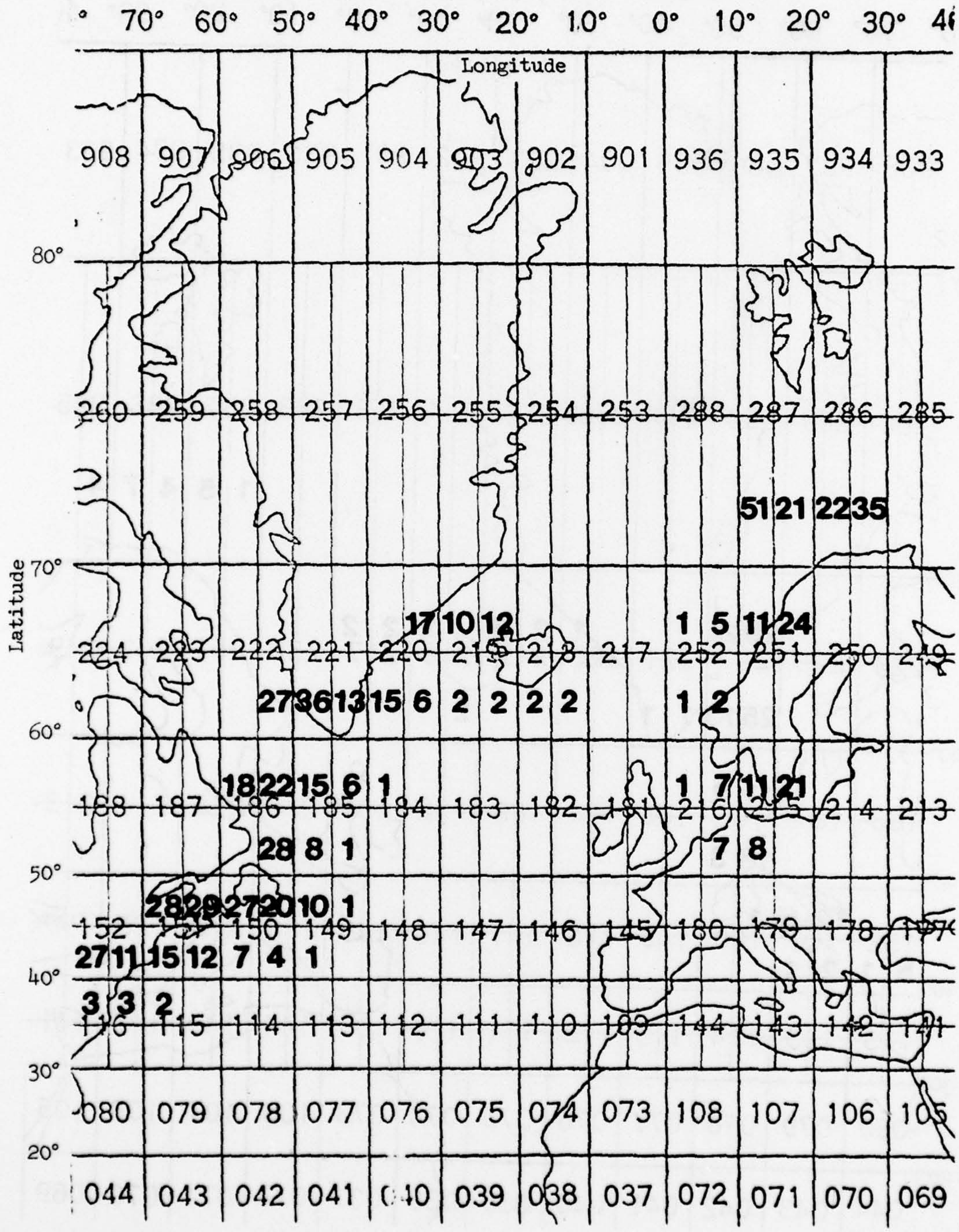
FIGURE 5E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



JANUARY

Air Temp.: -3°C to -6°C

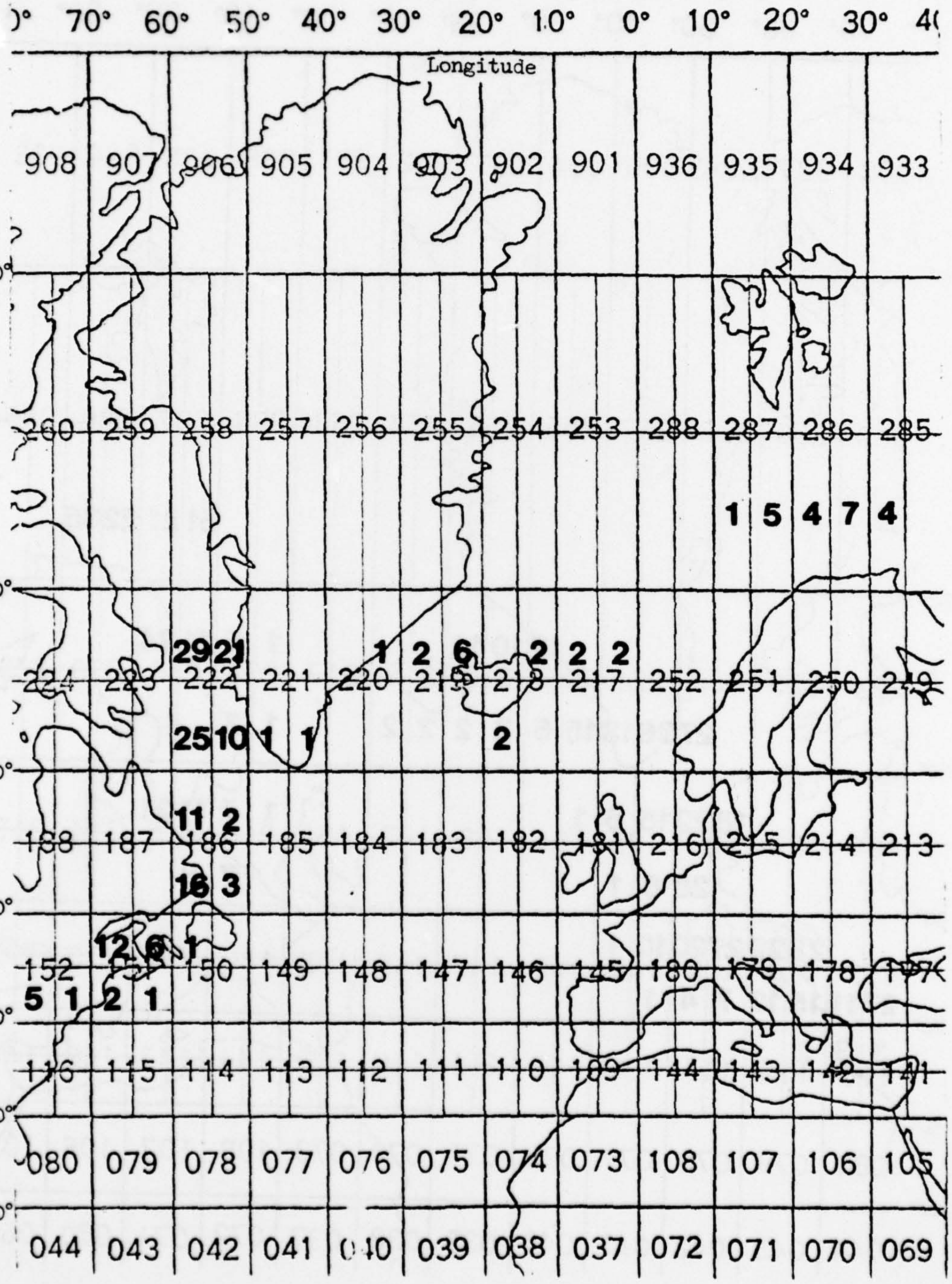
FIGURE 6E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



FEBRUARY

Air Temp.: -3°C to -6°C

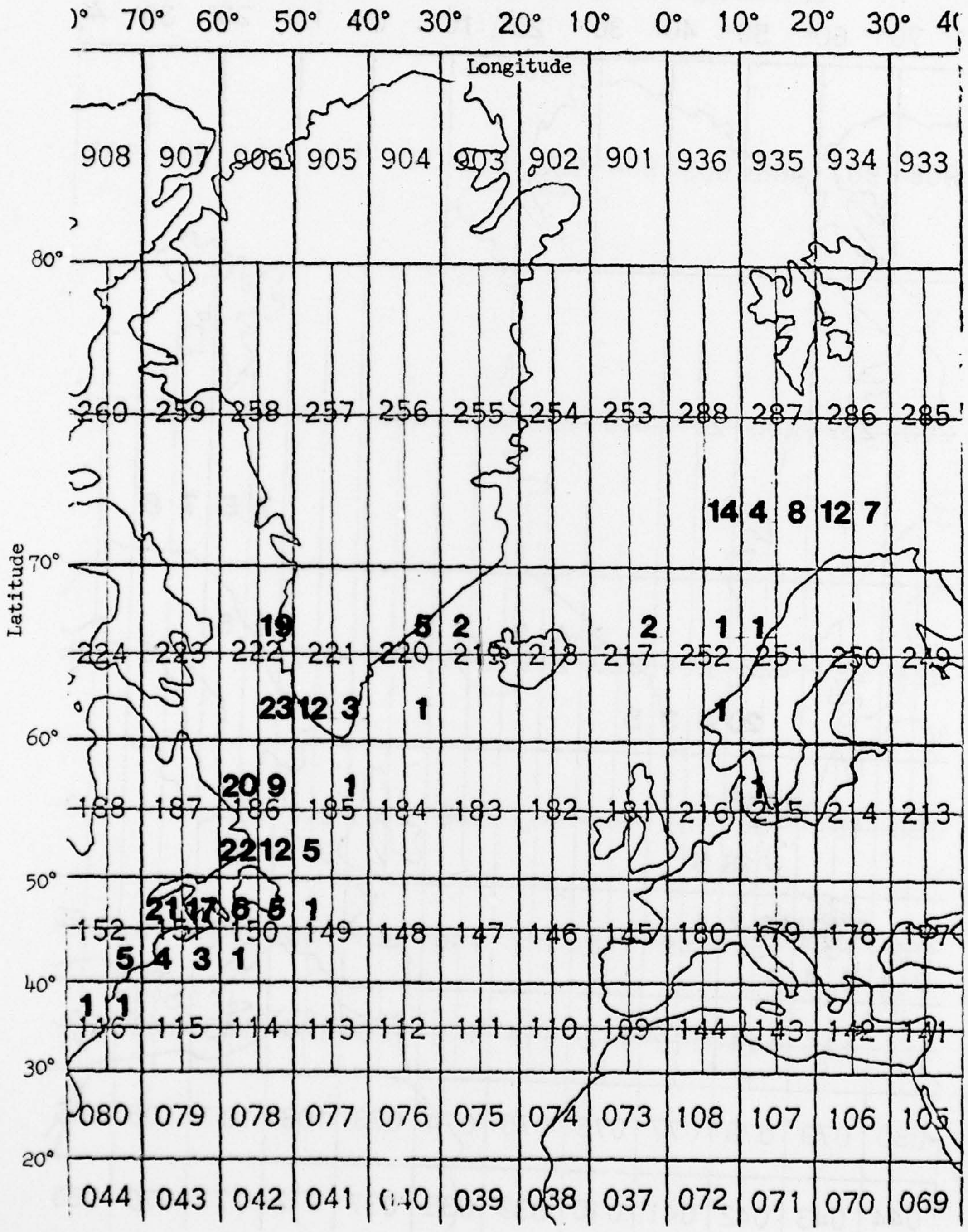
FIGURE 7E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



DECEMBER

Air Temp.: -6°C to -10°C

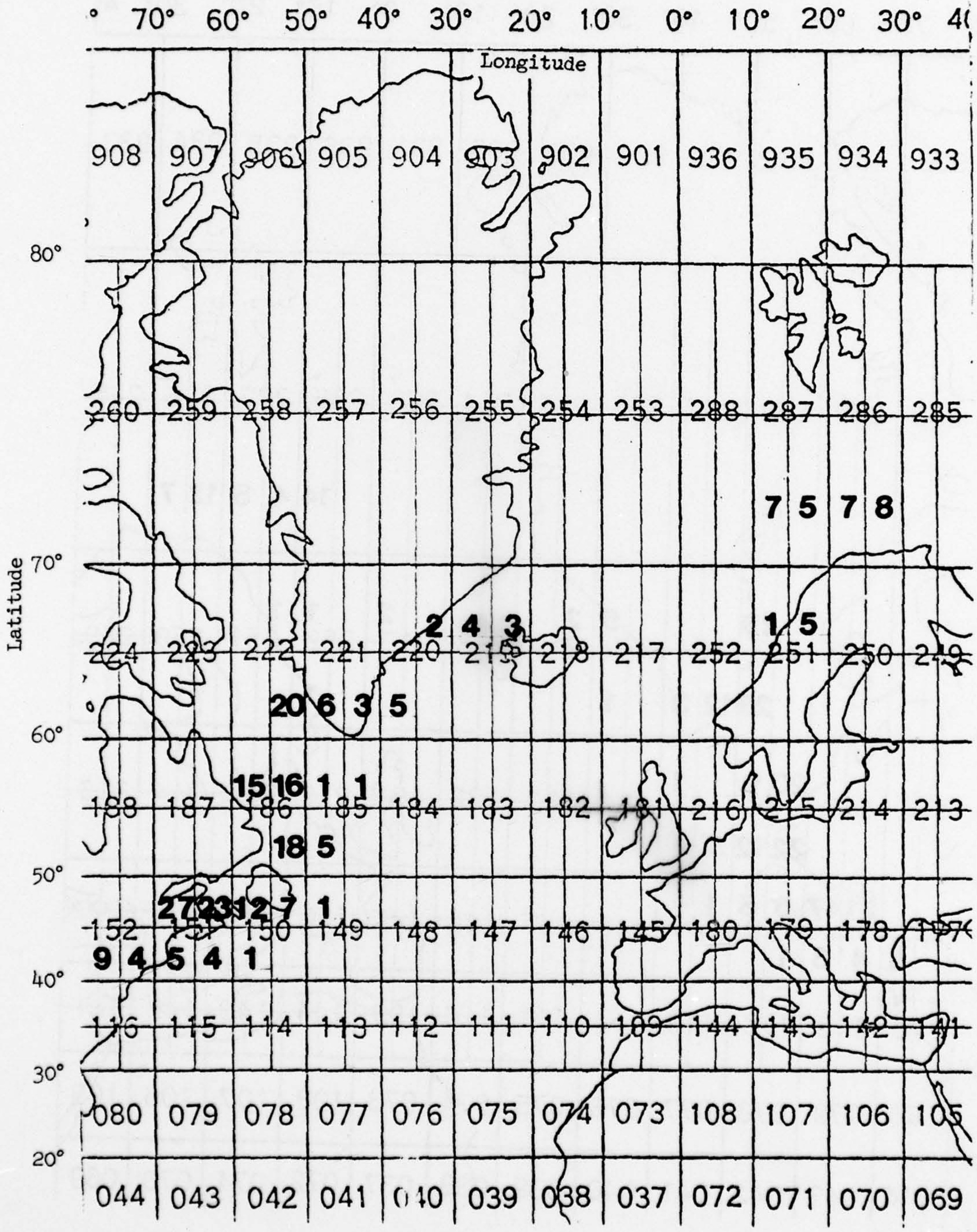
FIGURE 8E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



JANUARY

Air Temp.: -7°C to -10°C

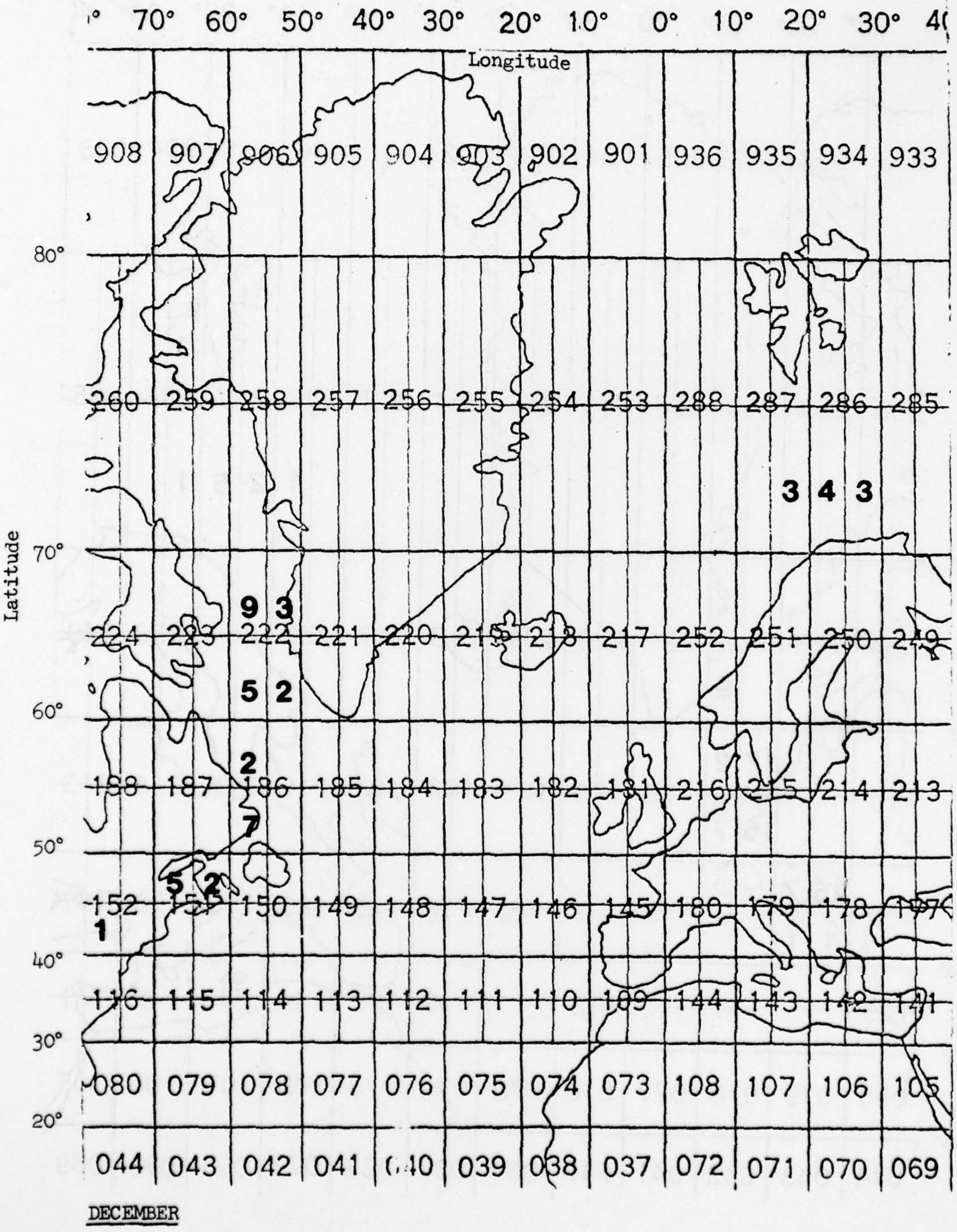
FIGURE 9E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



FEBRUARY

Air Temp.: -7°C to -10°C

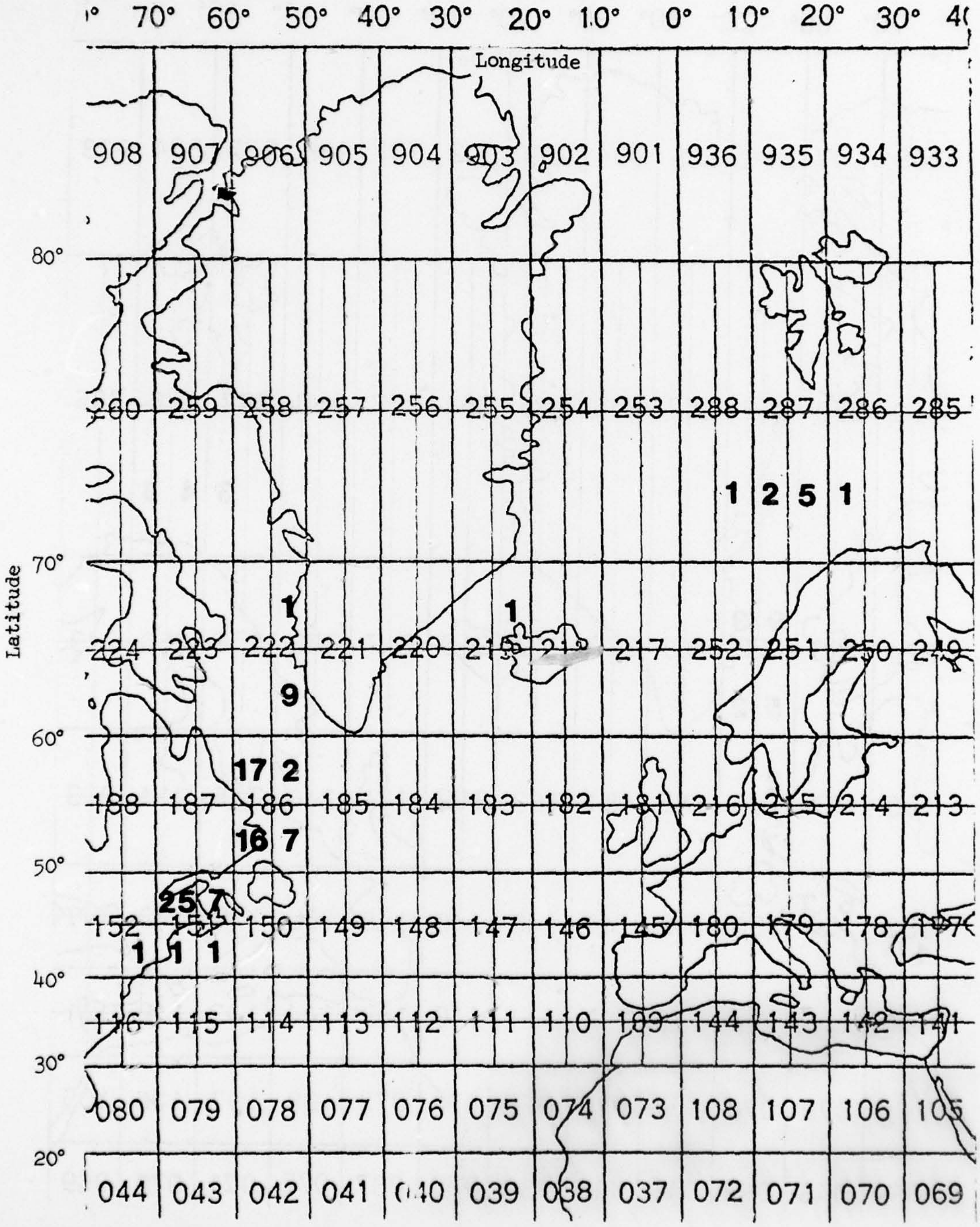
FIGURE 10E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



DECEMBER

Air Temp.: < -10°C

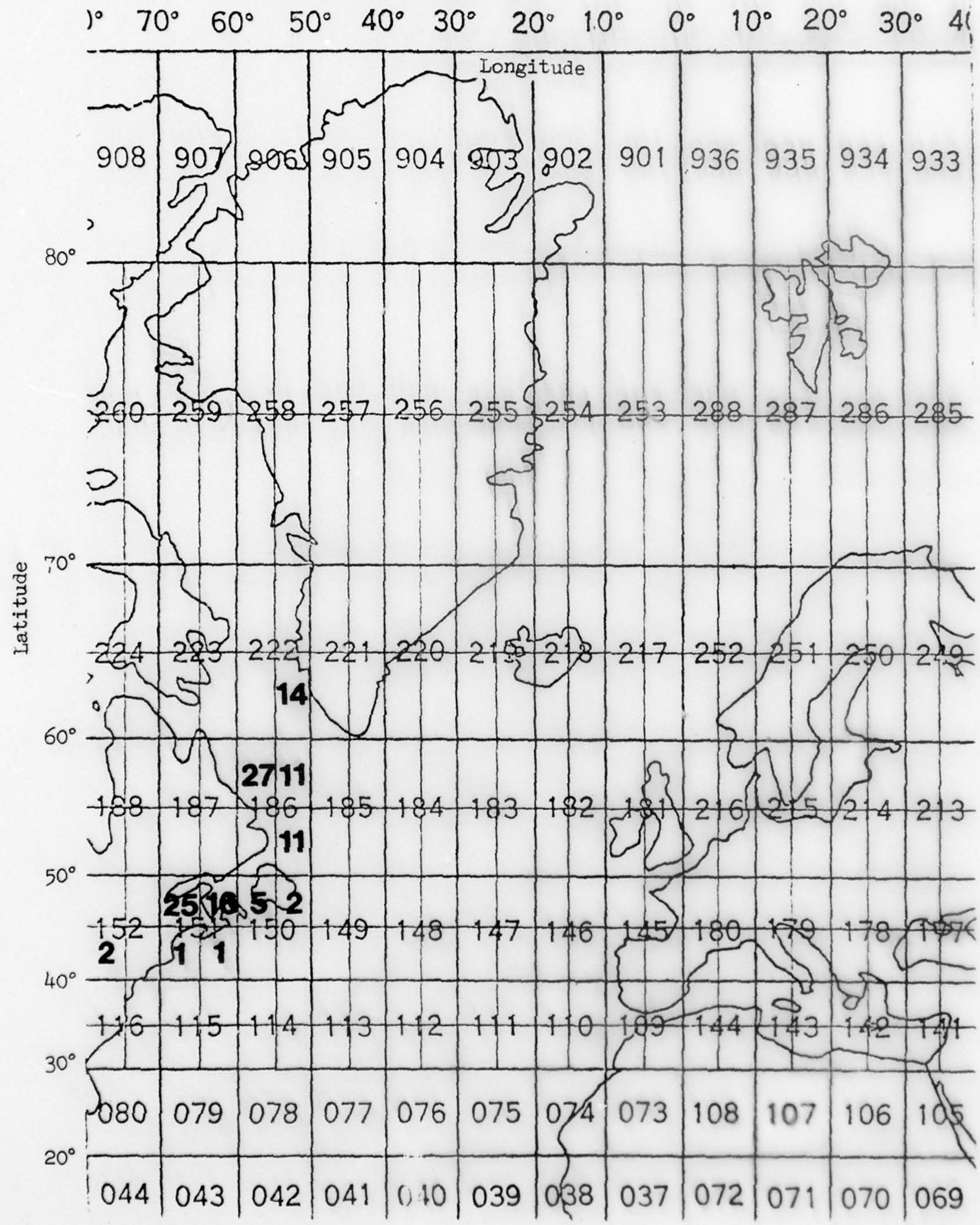
FIGURE 11E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



JANUARY

Air Temp.: < -10°C

FIGURE 12E: Frequency-of-Occurrence Distribution Maps of Freezing Air Temperatures



FEBRUARY

Air Temp.: < -10°C

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